Enhancing Energy Efficiency and Sustainability in Healthcare: Implementing a Heat Exchanger for Carbon Footprint Reduction

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Graduation project period: 21-04-2023 until 13-10-2023

Abstract—**This paper addresses the urgent need to optimize the GreenCycl facilities energy utilization, by harnessing heat from the effluent of three thermal washing-disinfection machines into the preheating of cold clean water. Currently for every washing-disinfection cleaning program, 60 times a week, 105 liters of water with a temperature of 60 °Celsius is discharged in the drain. This is not in line with the goals setup by the government and the mindset of GreenCycl.**

The study begins with a comprehensive analysis of the current situation, while documenting the properties and conditions. Subsequently concepts are generated with help of a morphological chart and a Harris profile is employed to select the most promising concept, this is further elaborated. Computational Fluid Dynamics (CFD) simulations are conducted to optimize the performance of the heat reclaiming system. Finally, the results of the CFD simulations are validated with experimental research.

By reintroducing 67% of the effluent back into the heat exchange system, a continuous flow across the heat exchanger of 35 liters per minute can be established with an operation duration of 2.5 minutes per washing-disinfection machine. Resulting in the heat reclaiming system to only operate when cold clean water is flowing through the HEX. If implemented at the GreenCycl facility, this innovation could potentially save approximately 7600 kW of electrical energy and reduce Carbon Dioxide emission by 1129 kg annually.

This study not only addresses a pressing environmental concern but also offers an easy and efficient solution with significant economic and ecological benefits.

INTRODUCTION

GreenCycl, in collaboration with Renewi, is investigating the possibility to reuse the heat in effluent of the medical washing-disinfection machines at the GreenCycl cleaning facility. The Dutch government wants to decrease the total Carbon emission and prompts all the industries to explore innovative approaches to enhance energy efficiency and sustainability [1]. Within this context, healthcare facilities have been identified as significant contributors to Carbon emission. A moderate portion of the Carbon emission is from heating water for hygienic equipment such as thermal washer-disinfection machines and sterilization devices [2]. As the healthcare sector is striving to the environmental goals setup by the government, the integration of technologies will become crucial in achieving Carbon footprint reduction.
The living lab of Greencycl and TU Delft are working together in a project called Evaluawaste. This is a project about reprocessing hospital waste to raw material. More information on GreenCycl can be found in Appendix A.

The cleaning facility at GreenCycl is of a large importance for the improvement of the overall sustainability of the instruments used in the operation theatre. Currently the life cycle of single use medical instruments are non sustainable, with the implementation of the cleaning facility at Greencycl the sustainability can be increased, notice figure 1. In the current situation medical instruments will be incinerated or thrown away. GreenCycl adds another option in the process, instead of the dirty instruments being send to an incineration plant, the dirty instrument are send to the GreenCycl facility and will be washed and disinfected. The instruments are cleaned, disinfected and disassembled and are transported to a recycling plant or parts will be reused in other deviced.

To facilitate the washing and disinfection of medical waste, GreenCycl has three Miele PG 8528 washer disinfection machined installed in the cleaning facility. These machines are continuous in operation, per machine 20 times a week, resulting in a high energy consummation and much potential for effluent heat reuse.

One technology that is promising in Carbon footprint reduction is a Heat Exchanger (HEX). Heat exchanger are facilitating the transfer of thermal energy between two fluids, this will offer great benefit in recovery of the thermal energy in the effluent of the washer-disinfection machines. Strategic implementation of HEX technology within the sewage line present a great opportunity for thermal energy recovery from the wastewater stream. The analyse of the current situation is given in Appendix B. The major focusing point of the graduation project is to install a heat exchanger into the cleaning facility that will reduce the power usage of the water boiler. Which currently consumes almost 5 kW of energy to heat the water needed in every single washing and disinfection program. On average the three machines are operational 60 times a week, accumulating the energy use of the boiler to a total of almost 16.000 kWh and an emission of 2200 Kg of Carbon Dioxide per year.

The hot water is used to wash and disinfect the instruments, in 5 different cycles using each 35 liters of water at a temperature between 30 and 95 degrees Celsius. 80% Of the total discharge is at least 60 degrees Celsius. In the current situation the water will be emptied at the same temperature in the drain. All the energy in the effluent will be lost which is not sustainable and does not comply with the circular healthcare economy.

35 Liters of water will be drained in a time span of about 30 seconds after every cycle (about every 7

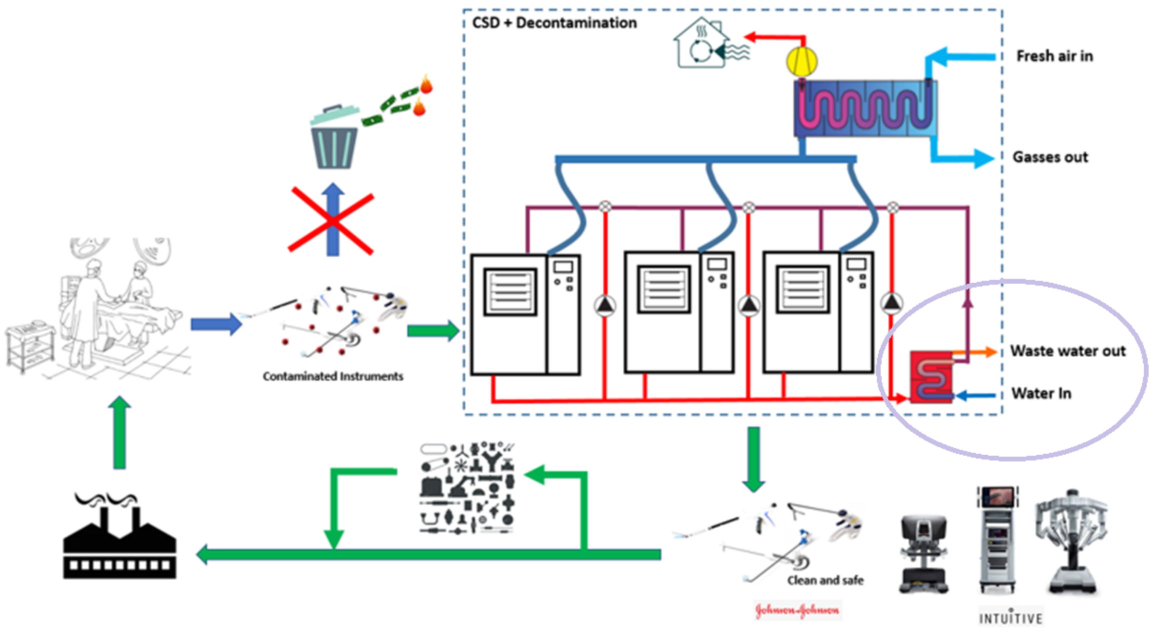


Fig. 1. Life cycle of unsustainable single use medical instruments indicated in blue arrows. The life cycle of more sustainable single use instruments is indicated by the green arrows. The contribution of the cleaning facility at GreenCycl is indicated in the blue dotted box and will provide the possibility to a circular use of single use medical instruments. The focus area of the thesis is indicated in the purple circle.

to 12 minutes), this results in a non continuous pulse like flow. Most heat exchanger are performing most optimally with a continuous flow. The external boiler tank is filled with cold water in the first 3 minutes after the washing-disinfection machines discharge their water and refiles the tank. Resulting in a time period of 3 minutes to exchange the heat from the effluent of the machines to the cold water leading into the external boiler.

Problem definition

The Dutch government wants to decrease the total Carbon emission and prompts all the industries to explore innovative approaches to enhance energy efficiency and sustainability. Within this context, healthcare facilities have been identified as significant contributors to Carbon emission, in the Netherlands the healthcare facility contribute to about 7% of total Carbon emission [3]. A moderate portion of the Carbon emission is from energy intensive processed involving clean and sterile working environment such as thermal washer-disinfection machines and sterilization devices. As the healthcare sector is striving to the environmental goals setup by the government, the integration of technologies will become crucial in achieving Carbon footprint reduction.

At present, the effluent from the washing machines, which carries a significant amount of thermal energy, is simply discharged into the drainage system. This discharge process takes only 30 seconds, resulting in a rapid and high mass flow rate occurring approximately every 7-12 minutes, creating a pulsating discharge pattern. Coupled with the cold water flow required to replenish the external boiler, which takes five times longer than the duration of the washing machine discharge, the operation of the currently installed heat exchanger is not optimal.

This thesis aims to design a system that optimizes the efficiency of the heat exchange system. The approach involves selecting a heat exchanger and designing a system that ensures a continuous flow of effluent, allowing for the pre-heating of cold water for the refilling of the external boiler. This system is primarily constructed using standard components and serves as the foundational framework for future (graduate) research. Ultimately, the final prototype should be versatile enough to serve as a demonstrative model.

The goal that is setup for this thesis is :
Design a heat exchange system for the sewage line of the GreenCycl disinfection facility to transform the pulsating water flow into a continues water flow, thus increasing transfer of thermal energy from the dirty water into the clean water.

Research question

One technology that is promising in Carbon footprint reduction is a Heat Exchanger (HEX). A heat exchanger facilitate the transfer of thermal energy between two fluids, this will offer great benefit in recovery of the thermal energy in the effluent of the washer-disinfection machines. Strategic implementation of HEX technology within the sewage line present a great opportunity for thermal energy recovery from the wastewater stream. Most heat exchangers are commonly used with a continuous flow of both heating and cooling water, the effluent flow of the washing machines are more pulse-like. This water flow behaviour address the research question:

Main research question:

How to implement an efficient HEX system into a pulse-like effluent flow in a sewage line of the GreenCycl disinfection facility?

Sub research questions:

1) **What is the most optimal flow speed for the heat exchanger?**
2) **What is the potential energy saving?**

Method

In Appendix B and Appendix D an analyse of the current situation is made and the location of the heat exchange and its in and outputs are determined, this resulted in the conditions and design requirements setup.

Conditions

The conditions are listed as a situation sketch. Which are applicable to the location of GreenCycl and the infrastructure.

- The dirty fluid consists primarily of water containing a small quantity of cleaning agent (Schülke Thermosept X-tra).
- Total volume of hot fluid 35 liters per machine cycle.
- Maximum volume of 35 liters of cold fluid.
- Both fluids must be kept separated.
- Cold water flow maximum 16 liters per minute.
- Cold water temperature ≈ 15 °Celsius
- Temperature of hot fluid up to 95 °Celsius.
- External boiler water requirement time maximum 3 minutes per machine.
- The stationary design shall not interfere with the workflow.

Design Requirements

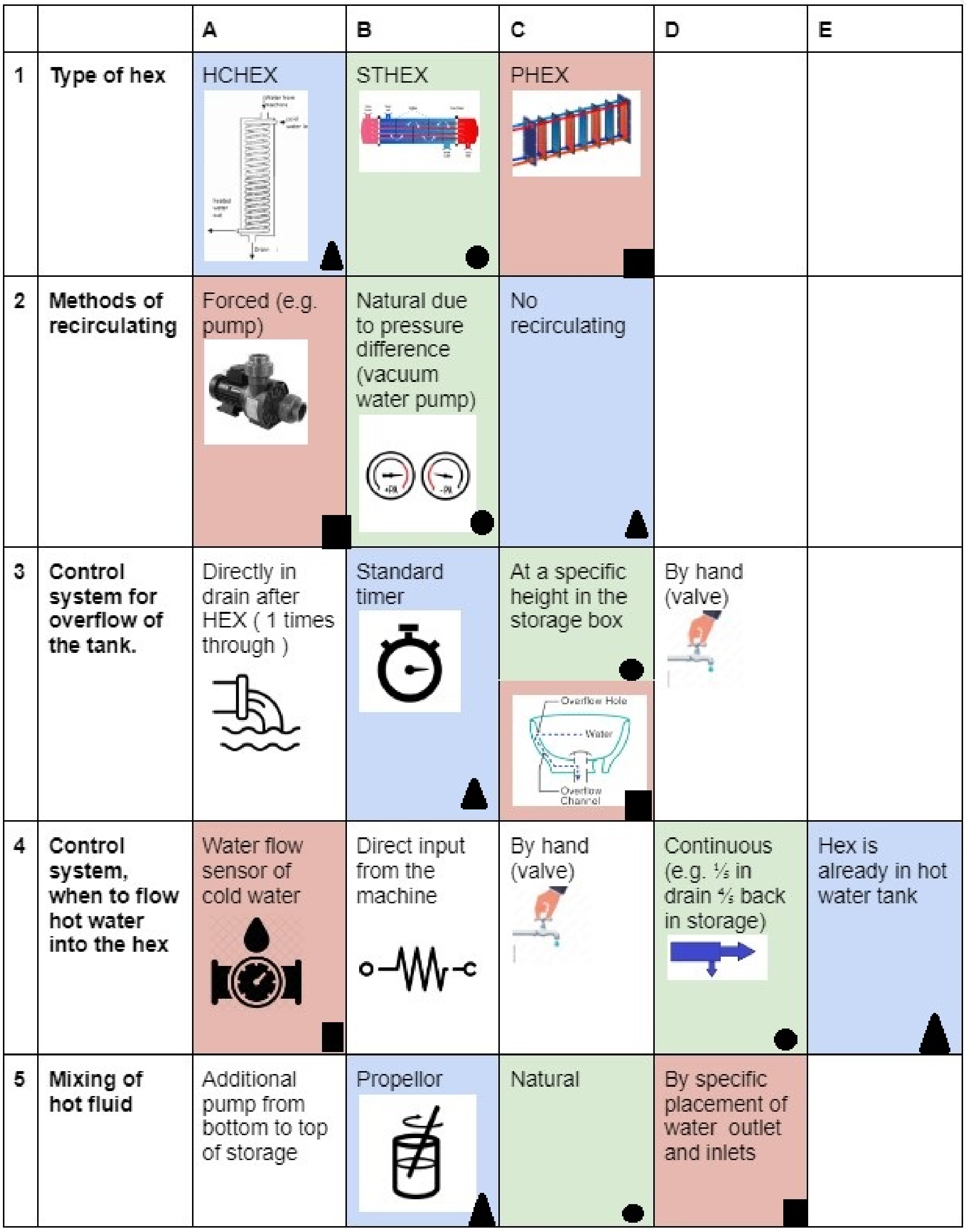
Some requirements are setup according to the SMART methodology to design the most promising concepts. For the validation criteria and the SMART methodology refer to Appendix C.

- Decrease the energy usage of the external boiler by 25% due to an increasing temperature of the water inlet.
- To ensure good working of the washing machine, the water flow should not be blocked nor a leakage should occur.
- The system should enhance CSSD employee safety by providing clean and safe work environment, for example, no sharp edges/parts.
- The design should meet the required standards and regulations to ensure safe operation.
- The HEX system has no influence on the operation time of the washing and disinfection machine itself.
- The system should not exceed a depth of 300 mm to minimize interaction with the working area of the employees in the cleaning and disinfection facility.
- Every part should be accessible within 5 minutes of disassembly for maintenance or repair purpose.
- Durable and corrosion-resistant material to withstand repetitive use and temperatures up to 100 °Celsius (Boiling point).
- The design (expect frame and tank) should be easily adaptable (temporary fixations) to contemplate future improvements and research.

Morphological chart

The morphological chart is presented in figure 2. As explained in Appendix E, Appendix F and Appendix G, three distinct types of heat exchangers are typically used for liquid to liquid heat exchange applications. Aiming for a high flow rate is crucial to maintain a high velocity of the fluids resulting in an elevated Reynolds number and consequently, high heat transfer coefficient. This can be achieved by circulation of the limited water volume to ensure a high heat transfer. This recirculating can be achieved by reusing "dirty" water from the HEX back into the heat exchange systems tank, either through an (external) driven force or natural, the principles of a siphon being one example of natural forced flow that is feasible.

Another critical consideration is the control of the system to prevent the tank from overflow. Due to varying timing between washing machine cycles, there exist a significant variance in the amount of water stored in the tank. If all the machines were to simultaneously



		A	B	C	D	E
1	Type of hex	HCHEX	STHEX	PHEX		
2	Methods of recirculating	Forced (e.g. pump)	Natural due to pressure difference (vacuum water pump)	No recirculating		
3	Control system for overflow of the tank.	Directly in drain after HEX (1 times through)	Standard timer	At a specific height in the storage box	By hand (valve)	
4	Control system, when to flow hot water into the hex	Water flow sensor of cold water	Direct input from the machine	By hand (valve)	Continuous (e.g. ½ in drain ½ back in storage)	Hex is already in hot water tank
5	Mixing of hot fluid	Additional pump from bottom to top of storage	Propellor	Natural	By specific placement of water outlet and inlets	

Fig. 2. Morphological chart used to determine the different concepts. Concept 1: Path indicated by "triangle".**A-C-B-E-C** ,focused on the most compact concept. Concept 2: path indicated by "circle". **B-B-C-D-C**, focused on the most passive capable concept. Concept 3: path indicated by "square". **C-A-C-A-D**, focused on the most active capable concept.

discharge their water and an error would occur, the machines will discharge its water, which might result in a overflow of the tank or clog up the washing machines outlet. To mitigate this risk, an solution might be to forego recirculating and have the water run directly through the HEX. Alternatively a timer and a liquid sensor can be installed in the tank to empty the tank e.g. every 5 minutes or when the water reach a certain threshold. Another option is a valve that can be opened by hand or install a overflow hole like in bathroom water basins. To make sure the heat of the mixed fluid is not convected to the top of the tank, mixing can be used to minimize this convection and provide a good temperature distribution throughout the entire tank.

Concepts

Utilizing the morphological chart as a guiding framework, three concepts are formulated, from top to bottom, concept 1, illustrated in figure 3 : **A-C-B-E-C**. In this configuration the heat exchanger is integrated into the tank resulting in the most compact of the concepts. There is no circulation and emptying of the tank is organised at predefined time intervals. A disturbance of the water can be achieved by a propeller installed in the tank to enlarge the total heat transfer.

Concept 2: depicted in figure 4: **B-B-C-D-C**. This design is chosen due to its passive application capabilities. Hot fluids enter from the right side of the picture into the tank storage. A drain located at the underside of the tank leads to the shell-tube heat exchanger. To achieve partial water recirculating, a pipe is installed downstream of the HEX and exploits a vacuum effect, pulling the water back into the beginning of the inlet of the heat exchanger. To avert overflow, a designated overflow hole at a specific height is installed. The mixing of the hot fluid remains natural.

Concept 3: depicted in figure 5: **C-A-C-A-D**. This concept is engineered with active application capabilities, designed to maximize heat extraction from the system. A plate heat exchanger is chosen for this application, a pump need to be installed to enable controlling the water recirculation. The recirculated water will be reintroduced into a strategic point in the tank to improve the mixing of the hot fluids. The velocity increase of the clean water will be checked with a flow sensor in the clean water pipes. This flow sensor also dictates operation of the pump to increase the mass flow rate of the hot water through the HEX.

Concept 1, figure 3 from top to bottom according to the morphological chart: **A-C-B-E-C**. This design introduces an integrated heat exchanger that employs a helical coil to channel the to be heated clean water through the hot fluids. The discharge from the washing machines outlet enters from the right side of the illustration. The hot fluid will be contained in the square tank, the inside is visible in the illustration. However, when the water remains stagnant, the Nusselt number remains low, resulting in a low heat transfer coefficient between the hot fluids and the to be heated clean water. To improve the movement of the water, a rotor should be strategically positioned between the helical coil heat exchanger to ensure water movement within the tank. This rotor is powered with help of an electric motor. When fluid is detected at the bottom half of the tank, an automatic timer will initiate a 5 minute countdown. Following this, a solenoid valve positioned underneath the tank opens, prompting the discharge of the water and all the water will flow out of the tank into the drainage. Additionally, a water sensor near the top of the tank can detect excessive effluent and will then trigger the solenoid valve to open and discharge the water to prevent obstruction in the water flow. A major advantage of this design over the other two is the size, the tank will provide a double function as a tank but also as the shell for the heat exchanger. A significant disadvantage of this design is the efficiency, the water in the tank is almost stationary resulting in a low Nusselt number and Reynolds number, which need to be as high as possible to ensure maximum heat transfer.

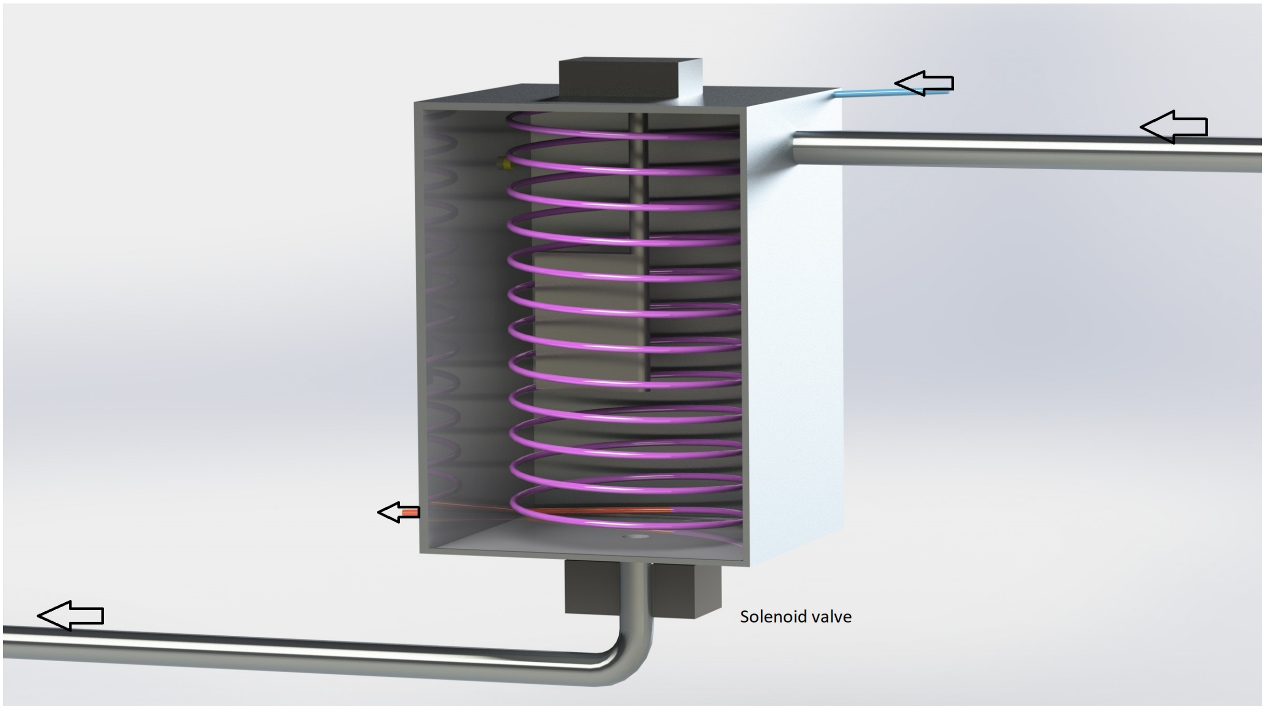


Fig. 3. Concept 1, shows a concept of the system with an integrated helical coil heat exchanger. Heat transfer will occur in the tank between the cold water in the coil and the hot water in the tank. After a certain time the solenoid valve will open and the dirty water will be discharged.

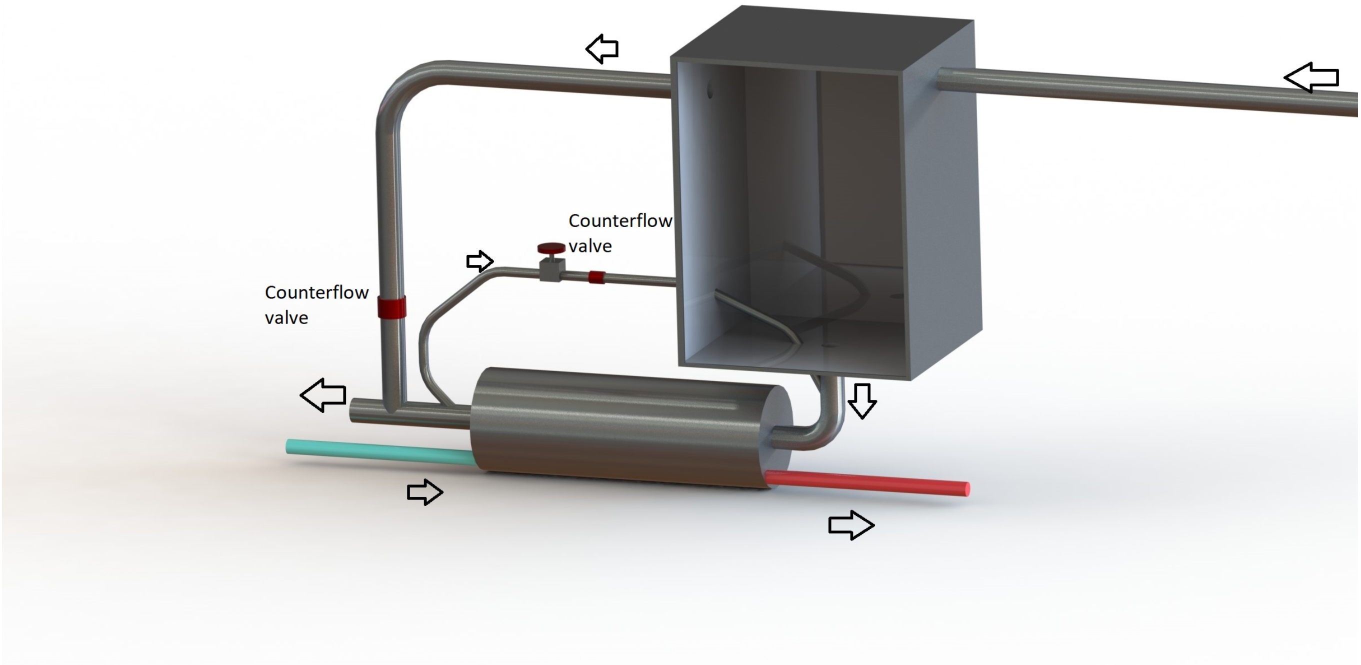


Fig. 4. Concept 2, shows a passive applicable STHEX with no sensors or other tools. Some of the hot water that transferred its heat in the heat exchanger will be re circulation due to the natural drag of the main stream while the remaining water is discharged in the drainage.

Concept 2, figure 4, from top to bottom according to the morphological chart: **B-B-C-D-C**. This design is focused mainly on passive working mechanism. The type of heat exchanger used in the design is a shell and tube heat exchanger (STHEX) which is less expensive in maintains then the plate heat exchanger (PHEX). By excluding complex software components, rendering the installation and upkeep of the design straightforward and budget-friendly. The input of the system is the outlet of the washing machines, connected on the right side of the picture. This hot effluent will be stored in the tank and immediately starts flowing out of the system through the heat exchanger. A recirculating tube, at the outlet of the heat exchanger, serves to reintroduce a portion of the water back into the system. Which is connected almost perpendicular to the tube underneath the tank. Positioned in such a manner that the water flowing into the heat exchanger creates a ”pull” effect. Draw fluid from the outlet of the heat exchanger through the recirculating tube back into its inlet. Within the recirculating tube, a valve is incorporated to adjust the hydraulic diameter, enable control over the amount of back flow into the heat exchanger. At the right side of the valve (colored in red) a counter flow valve is installed to prevent the flow of water through the recirculating tube instead of through the heat exchanger. To avert overflow, a overflow hole is installed in the tank at a certain threshold. Upon the water reaching this threshold, the water will flow through this hole into the drain. To prevent water flowing back into the system, a counter flow valve (colored in red) should be installed into the overflow tube. A notable strength of this concept is that there is no hard or software included in the design which could make it very maintenance friendly. A substantial disadvantage about this design is the non controllable flow of hot water through the shell-tube heat exchanger which could potentially result in loss of heated water into the drainage.

Concept 3, figure 5 from top to bottom according to the morphological chart: **C-A-C-A-D**. This concept is focused on active controllable system. A plate heat exchanger is commonly the most efficient heat transfer mechanism although the PHEX comes with some drawbacks. The inflow of hot effluent from the washing machines enters thought the pipe, on the right side of the figure, into the tank accumulating the water, simultaneously a minor stream of hot water will flow continuous through the heat exchanger facilitating preheating of the system. In the event of clean water flowing through the pipes of the heat exchanger, the flow sensor (indicated in yellow) will send a signal to the pump or solenoid underneath the tank. This action triggers the opening of the pump or solenoid valve and propellers the water through the PHEX. A portion of the water at PHEX outlet is recirculated via a pump, back into a strategic chosen

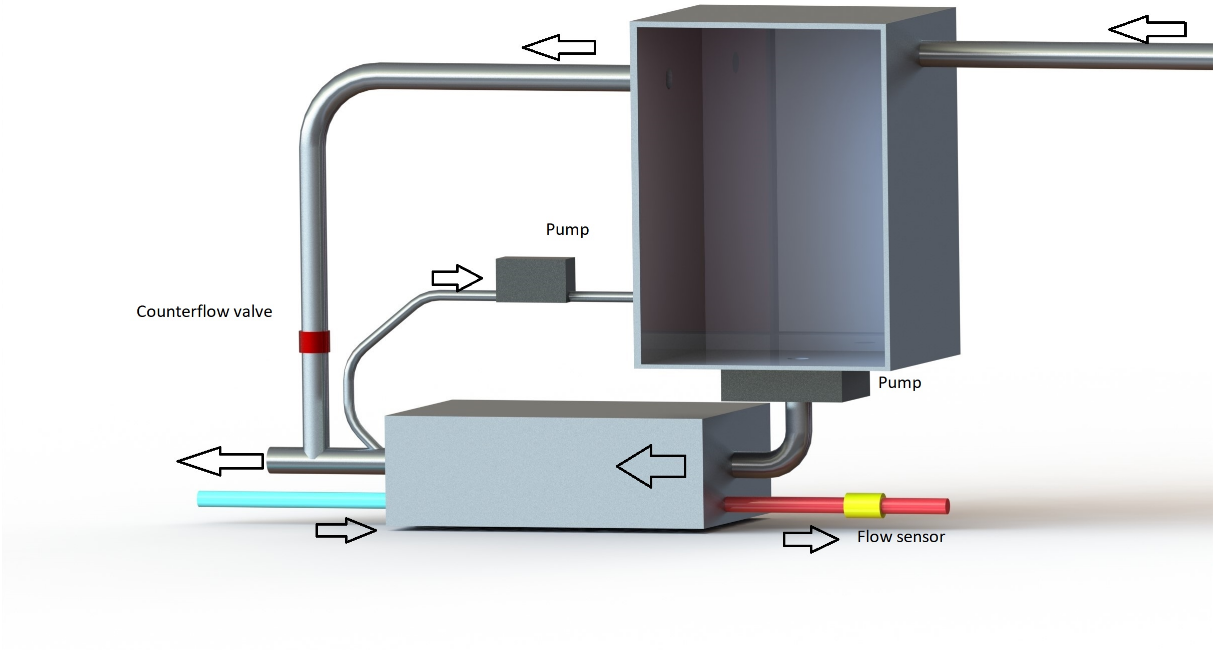


Fig. 5. Concept 3, shows a PHEX setup in which the water will be pumped through the HEX by means of a pump. Flow sensor integrated in the clean side pipe indicate water movement and start the pump for the dirty hot water.

location inside the tank. To avert potential overflow of the tank, a overflow hole is installed at a specific height, enabling excess water to be directly emptied into the sewage system. A counter flow valve (indicated in red) is located in the overflow tube to prevent sewage water flowing the opposite direction. A notable advantage of this design is the amount of adjustments that can be made to increase the overall performance of the system. A disadvantage about the design is the chance of blocking or leaking of the PHEX if debris is present in the effluent.

Harris Profile

The Harris profile, see table 1, table 2 and table 14 (in appendix H) are used to determine which of the concepts have the most potential to fulfill all the requirements. For the reasoning of the filled in Harris profile notice Appendix H. Concept 2 is the concept that have the most potential according to the Harris profile. The reason it scored really well in the Harris profile is because there were not much flaws (minus points) in the concept. With help of Appendix E, the coil heat exchanger is excluded from use due to its design limitations. Concept 3 shows great potential in the three highest weighing criteria, but a lot of point reductions resulted in the second place of this concept. The function of concept 3 with the solenoid or pump function to open the flow to the HEX is very promising in increasing the total performance of the setup.

TABLE 1. CRITERIA EXPLANATION OF THE HARRIS PROFILE.

Criteria	Explanation
Adaptability	The Greencycl lab wishes to do further research and implement more efficient items into the setup. It is therefore important to make parts of the design, be easily adaptable or add equipment to the setup.
Controllable efficiency	A controllable system should haves the possibilities to be setup to exchange energy in an optimum which will maximize the performance of the heat exchanged.
Base efficiency	A standard high efficiency has the possibilities to exchange more heat in the total system, which will decrease the costs and energy needs to heat up the water in the external boiler.
Complexity	How much regulation is possible both manually and programmable. This enlarge the Complexity of the whole system, making it more prone to errors.
Producability	What is the amount of non-standardised items included in the design. What items cannot be bought in the stores. Items that need to be specially designed and fabricated are expensive and have a long fabrication time.
Built in speed	The setup needs to be installed into a continuous working washing line, thus it is important that the washing line can continue as fast as possible.
Costs	To produce the setup and maintain the setup, the production costs should be low.
Maintenance	The system needs to be built into an already existing washing line, which is in continuous use. It is important that the setup does not need much maintenance and is very robust to ensure no error would occur. Which can result in a complete stop of the washing line.
Size	The system needs to be placed inside the dirty room of the washing line, this means that relative limited space is available.

TABLE 2. HARRIS PROFILE

	Concept 1				Concept 2				Concept 3				Weight
	- -	-	+	++	- -	-	+	++	- -	-	+	++	
Adaptability			+				+	++			+	++	5
Controllabe Efficiency		-				-					+	++	5
Base efficiency	- -	-					+				+	++	4
Complexity			+	++			+	++		-			3
Producability			+				+	+			+	+	3
Built in speed			+	+		-				-			2
Costs			+				+	+	- -	-			2
Maintenance		-					+	+		-			2
Size			+	++	-	-				-			2
Total Score	**13**				**23**				**21**				

Concept combination

Some improvements in combining the concepts idea of concept 2, figure 4, and concept 3, figure 5 are possible. A selection between the PHEX and the STHEX need to be made, while both HEX are very promising and either have their own limitations and advantages. The disadvantage of the tube and shell heat exchangers are limited while the disadvantages of the PHEX are harder to overcome. While looking into the washing machines water reservoir after the cleaning is done, some small parts of material can be found that could clog the PHEX, therefor it is decided to select the STHEX for this system. The shell and tube heat exchanger that is selected with help of the supervisor is an Elecro 122kW TITANIUM shell and tube heat exchanger.

To enhance the circulation within the heat exchanger (HEX) on the dirty side, the inclusion of a pump is necessary. This pump will draw water through the HEX, increasing turbulence and heat transfer. Following the pump, a diverter can be added to allow for two options: either recirculating the water back into the tank or directing it into the sewage system.

In Appendix J, simulations have been conducted to identify the most optimal flow velocity through the HEX. Once this optimum flow velocity is determined, it becomes possible to calculate the required amount of recirculation and set the pump velocity accordingly. With the completion of these simulations and the selection of the appropriate pump type, the final design can be manufactured.

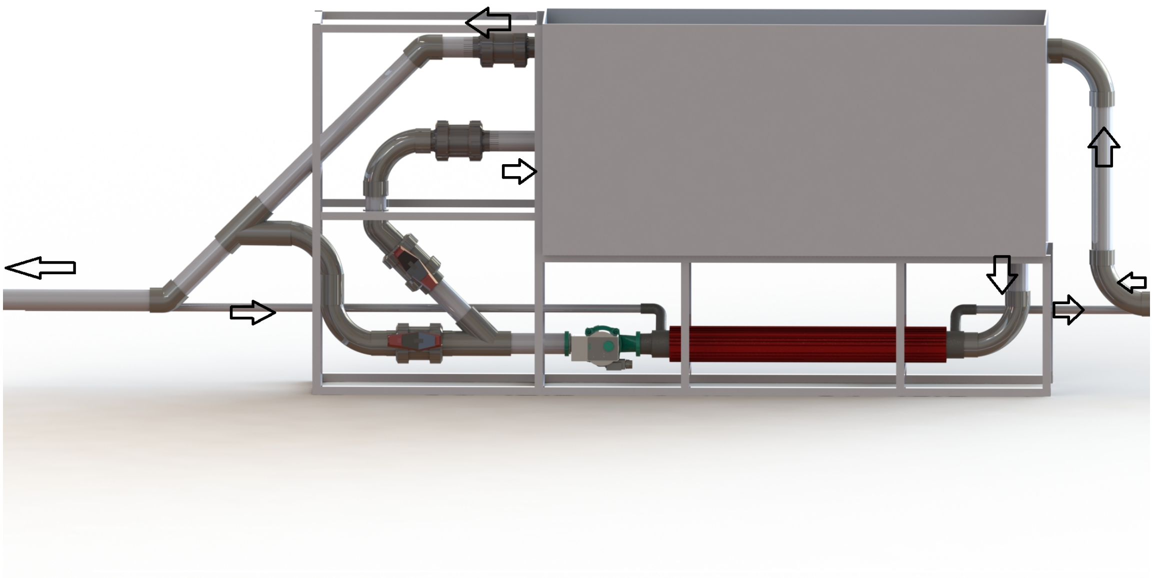


Fig. 6. Final solidworks design of the stationary GreenCycl effluent heat retracting system. The input of the dirty water is indicated at the right side of the figure. Following the arrows will indicate the flow of the hot water.

METHOD OF EXPERIMENTATION

The primary objective of this test is to continuously monitor the heat transfer between the two main water flows. The experiment involves four K-type thermometer sensors as illustrated in Figure 7. The heat transfer is determined by measuring the temperature difference between the T_Clean_in and T_Clean_out, which quantifies the energy transferred into the cold water. Consequently, the cooling of the dirty water is indicated by the temperature difference between T_Dirty_out and T_Dirty_in. These measurements provide insight into the total energy transferred to the clean water and the reduction of energy within the effluent.

Fig. 7. K-type thermocouple sensor location used for determine the amount of heat being transferred between the mediums.

The experiment is conducted without the washing-disinfection machines. Instead, the living lab of GreenCycl provides the possibilities and equipment to do this experiments. To conserve energy and water, the effluent discharge from two simultaneously operating disinfection washing machines is tested 3 times, as is the heat transfer of a single discharge of a disinfection wash-machine.

To facilitate measurements, two reference lines are marked within the tank using a permanent marker. These lines indicate the 35-liter and 70-liter volume levels in the tank. For the initial valve calibration, 70 liters of cold water is stored inside the tank. Although the liquid sensor detects the presence of water, it does not send a signal until a push button is activated. This push button is only included for the testing phase for water to be collected inside the tank. Pressing this button will initiate the pump, which runs for approximately 4.5 minutes. This duration corresponds to the time needed to supply the cold water at a rate of 16 liters per minute for refilling the external boiler. Subsequently, the water is pumped through the system, emptying the tank. The cold water collected during this calibration process is discharged at the drainage outlet. Once the valves are calibrated, the testing phase can begin.

The sensors utilized in this experiment are all K-type thermocouple. Data collected from these sensors will be transmitted by a micro controller (Arduino), and logged in an online database,see figure 9, for the code see appendix L, this database will show and save the data to be used for the calculations. Additionally, a SST liquid sensors is employed to sense the liquid levels.

Fig. 8. Overview of the setup for the experiment at the GreenCycl Living lab facility. Underneath a close up of the valves (blue), the heat exchanger (red), the pump (green) and the display of user interface (with blue and yellow buttons).

During testing, it is important to note potential deviation that may arise due to constraints such as limited water pressure, due to the external boiler location and the location of the tap for the cold water. To track the mass flow rate of cold water, a bucket equipped with scales are employed. The process involves filling the bucket with the heated cold water for a time period of 1 minute, followed by replacing it with another bucket.

Fig. 9. Arduino IOT online portal overview. Left above indicates T_Dirty_in, right above indicates T_Dirty_out, left bottom indicates T_Clean_in and right bottom indicates T_Clean_out.

The conducted experiment is split into different steps that are depicted below:

1) Close the valve leading to the drainage.
2) Pour half the desired volume into the tank and start the pump to initiate recirculation.
3) Monitor the temperature of the water and add colder or hotter water as needed until the water levels are aligned with the mark on the inside of the tank.
4) Note the time and disconnect one of the thermocouple sensors (until online portal reads 0) and re connect.
5) Open the valve for the cold water flow.
6) Open the drainage valve.
7) Start a 2.5-minute timer.
8) Continuously observe the water levels in the buckets and replacing them when necessary.
9) After one minute remove the bucket of the heated cold water and read the scale in the bucket.
10) The pumps stops after approximately 2.5 minutes, at which point the tanks should be empty.
11) Note the time and disconnect and connect one of the thermocouple sensors again.

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Hypothesis: .
In section *simulation results* it has been determined that the water need to be recirculated 3 times. Through simulations, the temperature difference for a single circulation is calculated. In the case of the hot water flow, with a flow rate of 35 liters per minute on the dirty side, a specific amount of energy is transferred, resulting in a temperature decrease of 6.7 °Celsius. In Equation (1) the thermal energy is denoted to be linear with the temperature difference. It is assumed that the quantity of thermal energy transferred remains constant throughout the three re circulations, resulting in a cumulative temperature decrease of 13.4 °Celsius, averaging to a hot water temperature of 53.3 °Celsius. It is known that the efficiency of thermal energy transfer is dependent on the temperature difference. The average temperature expected of the hot water is round up to 54 °Celsius. The outflow temperature of the hot water is expected to be, on average, 5 °Celsius cooler than the inflow temperature of the hot dirty water due to a lowering heat transfer efficiency attributing to a reduced temperature gradient. The hypothesis temperature of the hot water outflow is 49 °Celsius.

The temperature gain for the cold water is expected to be three times the temperature different between the hot dirty side. With 35 liters of hot water recirculating three times compared to 35 liters of cold water, assuming that all the thermal energy ”lost” from the hot water is transferred to the cold water, this results in an outlet temperature for the cold water averaging 35 degrees Celsius. If the hypothetical values are filled in, in equation (1), this result in an energy transfer to the cold water of 0.6 kWh every cycle. Concluding to 2.4 kWh per washing program and energy need of the boiler decreasing by approximately 48 %.

Design Result

Due to the placement of the heat re winning system the dept of the system should not exceed 300mm in order not to interrupt the working flow of the dirty room. The final design, based on the Harris profile, will incorporate some key features from concept 2 and concept 3. The key features from concept 2 that will be incorporated into the final design are the STHEX, the counter flow valve and valve in the recirculating loop. The pump of concept 3 for the recirculation tube is excluded from the final design. In alignment with Shen et all (2014) [4] the pump situated underneath the tank in concept 3 will be moved from the inlet of the HEX to the outlet of the HEX, this modification is made to enhance the overall system efficiency.

However, the flow sensor indicted in concept 3 is not incorporated into the final design due to its high cost and relatively low efficiency gains. To prevent dry running and potential pump damage, a water sensor will be installed inside the tank. This sensor will trigger the pump to start and stop when the tank is nearly empty or being filled. An overflow hole, key features in concept 2 and 3, is incorporated into the design to ensure no overflow of the tank is possible, this overflow can occur due to the washing machines receive an error and release all its water directly into the sewage without the tank being emptied. Subsequently the overflow hole can be used as regular effluent flow stream if the pump is blocked for example. To decrease the mass velocity of the cold water flow a valve is already installed in the

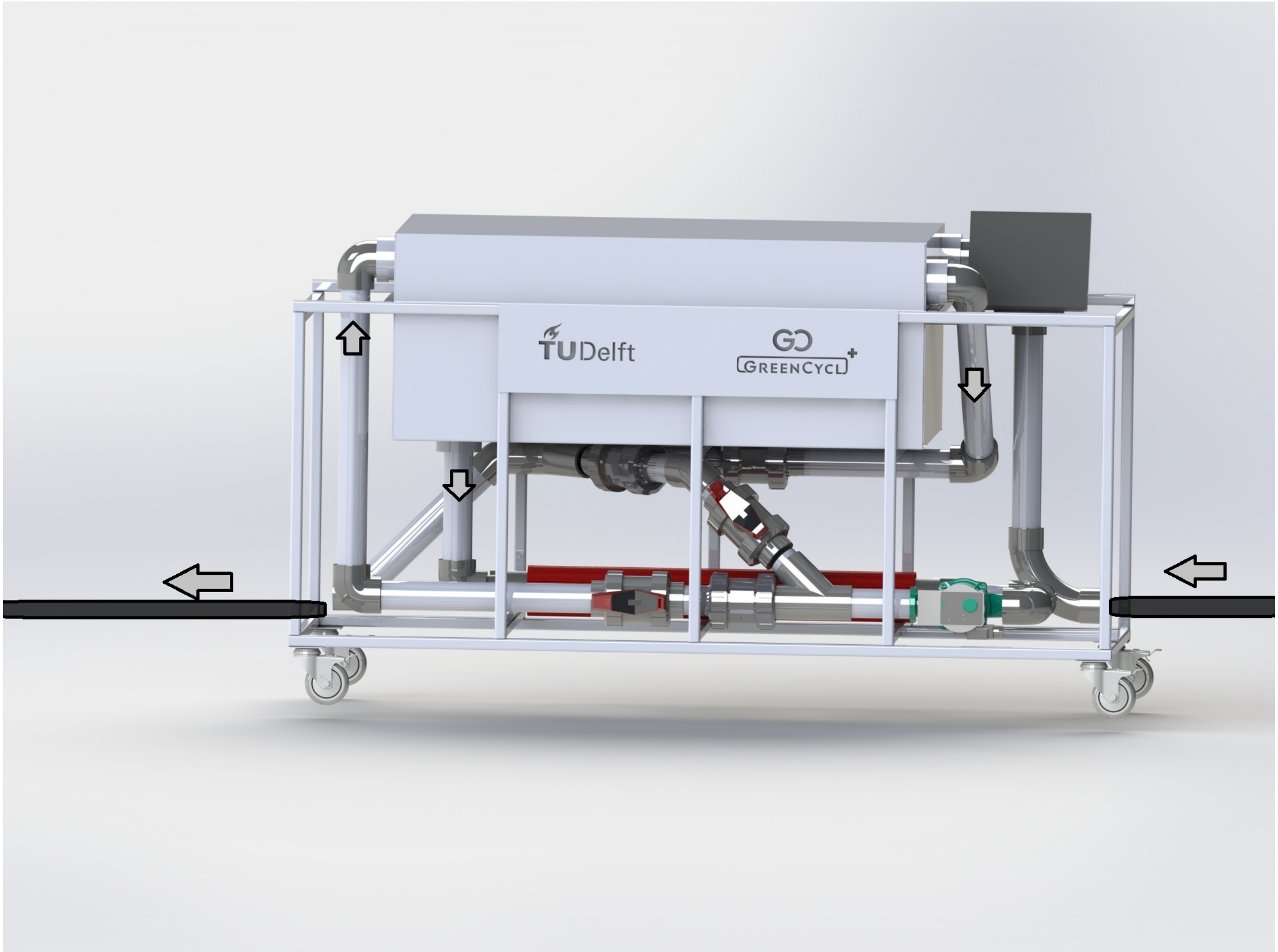

Fig. 10. Final Solidworks design of the mobile GreenCycl effluent heat retracting system. The arrows indicate the flow of the dirty water. The water is collected in the tank and flow through the pipes into the STHEX due to the force exhibited by the pump. The water reaches a 45 degree T-split and either passes straight back into the tank or lead outside the system into the drainage.

piping system.

Through numerical calculations, see Appendix I, an finite number of simulations can be conducted in Solidworks, see Appendix J, an optimal flow velocity for the pump has been determined. The selected pump, a *Yonos PICO 25/1-4-130* heating circulation pump, with a maximum flow rate of 45 liters per minute, adjustable via a rotating knob on the pump. Additionally, this pump will display the system's mass flow rate, this facilitate the alignment of the pumps characterisations found in Appendix J. The pump is designed to be in all time total contact with water, therefore a siphon like design is made to dip the pipes and the pump beneath the sewage output height.

The final design and its flow directions are depicted in figure 6. Given the fluids maximum temperature of 95 °Celsius, conventional PVC piping is not suitable due to their maximum working temperature of 60 °Celsius. Therefore Polypropylene (PP) components must be chosen due to their resistance to the high temperature. The primary drainage pipe used in the design are all 50 mm in diameter. The 45 °T-split at the outlet of the hex should divert 33 % of the water into the sewage while the other 67% of the water should be lead through the circulation tube back into the tank. To control this diversions two valves are incorporated to find the perfect ratio. This accounts to 10 to 15 liters per minute of water being drained into the sewage and should consequently result in the tank being emptied at the time the clean water filled the external boiler back up.

The tank will feature four PP pipe connection for reservoirs to attach the PP piping's to the tank. The frame of the tank is designed to embrace and secure the important parts of the system. A final adaptation to add wheels to the design is made to make the system moveable. The final design is therefor slightly adapted see figure 10.

Simulation Results

In table 3, the values are depicted that are used in the simulations.The hot water flow is simulated at 60 °Celsius, the cold water flow is simulated at 15 °Celsius. The figures resulting of the simulations are depicted in Appendix J. An example of the figures of the simulation can be seen in figure 11 .

TABLE 3. VALUES USED FOR THE SIMULATIONS TO FIND THE MOST OPTIMAL FLOW VELOCITY FOR THE DESIRED HEAT EXCHANGER.

Cold water flow (L/min)	Hot water flow (L/min)
	10
	20
12	30
16	35
	40
	45
	50
	60
	70

In table 4, the results of the outlet temperature of the clean water simulations are presented. For the HEX output temperatures of the dirty water with initial 60 °Celsius, refer to table 5. The temperature difference between the flow of 40 liters per minute and the 30 liters per minute flow is 0.93 °Celsius for the 12 liter per minute flow and 0.77 °Celsius for the 16 liters per minute flow although this does not reach the predefined threshold. Comparing the temperature difference between the 40 and 50 liters per minute hot water flow will result in a temperature difference of 0.60 and 0.68 °Celsius. This result hovers around the threshold of 0.625 °Celsius increase for every 10 liter per minute pumped. Considering potential fouling that can reduce the performance and the necessity to maintain a positive energy balance. For each operating machines, 35 liters of cold water need to be heated this should take between 6 minutes 30 seconds to 9 minutes. To achieve optimal performance in the HEX system, assuming that the three machines discharge their effluent simultaneously into the tank between 260 and 360 liters of water passes through the HEX. This implies that the 105 liters of water, should be recirculated for 3 or 4 times. This results in **10 to 15 liter per minute need to be drained into the sewage to empty the tank simultaneously with the external boiler being filled.** Due to recirculating 66% of the dirty water back into the system, the mean temperature of the HEX inlet will be decreasing over time. However, the pumping power remains the same.

TABLE 4. HEX OUTLET WATER TEMPERATURE IN °CELSIUS OF THE CLEAN SIDE.

		Cold water flow [L/min]	
		12	16
Hot Water Flow [L/min]	10	-	21.21
	20	29.02	26.87
	30	30.48	28.36
	35	30.97	28.82
	40	31.41	29.23
	45	31.69	29.51
	50	32.01	29.91
	60	-	-
	70	32.68	30.68

TABLE 5. HEX OUTLET WATER TEMPERATURE IN °CELSIUS OF THE DIRTY SIDE.

		Cold water flow [L/min]	
		12	16
Hot Water Flow [L/min]	10	-	48.50
	20	49.95	49.65
	30	52.40	51.68
	35	53.31	52.54
	40	53.87	53.15
	45	54.49	53.82
	50	54.85	54.22
	60	-	-
	70	56.09	55.58

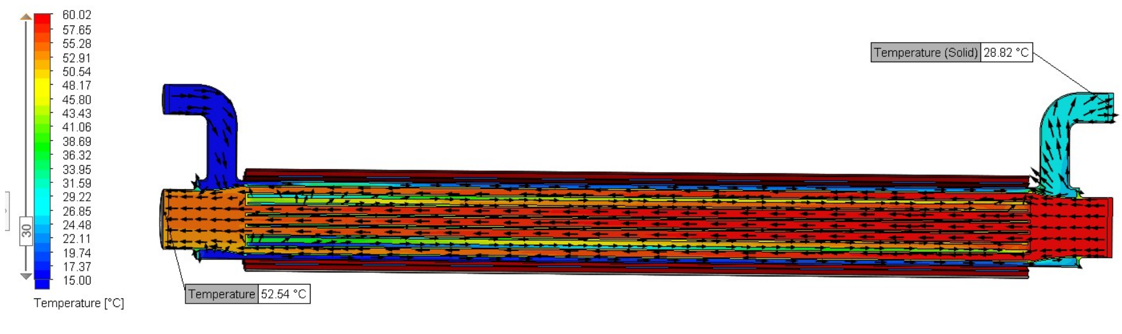

Fig. 11. CFD simulation on Solidworks with a 60 °Celsius 35 L/min hot water flow and 16 L/min 15 °Celsius cold water flow.

Experimental Results

The average temperatures measured during each test are summarized in table 6 (for the 35-liter test) and table 7 (for the 70-liter test). These test averages are joined in table 8, and depicted in figure 12 which also includes the initial hypothesis for reference.

TABLE 6. Test results in °Celsius of the 35 liter hot water test.

	Test 1	Test 2	Test 3	Average of the tests
Average T_Dirty_in	57,3	57,6	53,8	56,2
Average T_Clean_in	24,1	23,7	25,9	24,6
Average T_Dirty_out	54,6	50,9	50,2	51,9
Average T_Clean_out	47,1	46,7	46,4	46,8
Δ T_Clean_in and T_Clean_out	23,0	23,0	20,5	22,2

TABLE 7. Test results In °Celsius of the 70 liter hot water test

	Test 1	Test 2	Test 3	Average of the tests
Average T_Dirty_in	51,6	51,3	55,0	52,6
Average T_Clean_in	21,8	22,9	26,5	23,7
Average T_Dirty_out	48,6	45,9	47,6	47,4
Average T_Clean_out	46,9	44,9	44,6	45,5
Δ T_Clean_in and T_Clean_out	25,1	22,0	18,1	21,7

The bucket tests aiming to understand the rate of mass flow of cold water, shown result ranging from 8 liters per minute to 12 liters per minute. To calculate the efficiency of the system, the total heat transfer from the hot dirty fluid to the cold fluids is calculated. This calculation considers the thermal energy transferred to the cold water, taking the variations in cold fluid mass

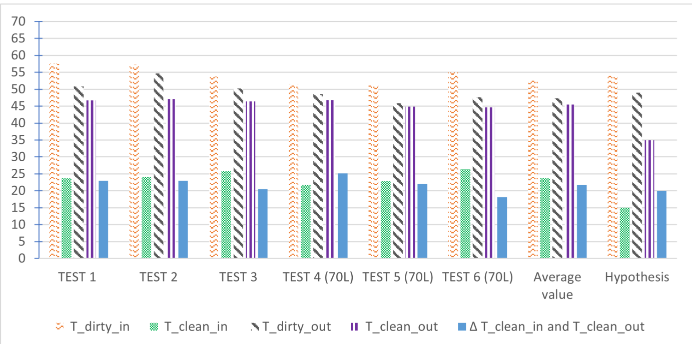

Fig. 12. Column overview of the experimental results.

TABLE 8. Results of experiment depicted in °Celsius compared to the hypothesis.

	Average 70 L test	Average 35 L test	Average of test	Hypothesis
Average T_Dirty_in	52,6	56,2	54,4	54
Average T_Clean_in	23,7	24,6	24,2	15
Average T_Dirty_out	47,4	51,9	49,6	49
Average T_Clean_out	45,5	46,8	46,1	35
Δ T_Clean_in and T_Clean_out	21,8	22,2	22,0	20

flow into account. Two scenarios are calculated: one with a minimum mass flow velocity of 8 liters per minute (resulting in 20 liters in total) denoted as Vl, and another with a maximum mass flow velocity of 12 liters per minute (resulting in 30 liters in total) denoted as Vh. The average Clean_out temperature across all tests, provides an estimate of the total heat transfer within the system for a single washer-disinfection effluent discharge. Formula (1) is used to calculate this energy transferred.

$$Q= V*\rho*c*\Delta T /3600 \text{ Kw} \quad (1)$$

ρ = 997 kg/m^3
c= 4.187 kJ/kg/K
Vl= 20 Liters
Vh= 30 Liters
Vdl= 35 Liters
Vdh= 45 Liters
Ql= 0.51 kW
Qh= 0.77 kW
Qs= 1.22 Kw
Qdl= 0.40 Kw
Qdh= 0.40 Kw
Δ T = 22 °Celsius
Δ Td= 10 °Celsius

According to cold flow temperature difference is the efficiency between 42% and 63%. The efficiency increase of the boiler according to the hot water temperature difference is between 32% and 43%. This results in a reduction in power consumption of average 47%.

Discussion

Design discussion

The design requirement, which mandated a maximum system depth of 300 mm, has been revised. The heat exchange system has a depth of 500 mm, enhancing its stability and mobility features. All components within the device are engineered to endure high temperatures of up to 100 °Celsius, with the exception of the pump, which has a maximum operating temperature of 95 °Celsius. Worth noting that finding a price-friendly adaptable water pump capable of withstanding temperatures of 100 °Celsius is a challenge, likely due to potential water phase changes leading to unpredictable variations in pressure and fluid behavior.

In this system, all waterway fittings are securely linked using hose clamps, threaded connections, or press-fit components, which are fastened to the frame using clamps. This setup facilitates rapid assembly and repairs but also offers the flexibility for future improvements or adaptations through research.

Even if the prototype is installed in the dirty room, the device would not be classified as a medical device. The dirty side of a cleaning facility is subjected to other regulations and guidelines related to cleaning and decontamination in healthcare settings. All the components of the heat exchange system are inspected for sharp edges hazardous parts. All the components are finished smooth and no sharp or hazardous components are present except from the tyraps needed for guidance of the wires and fastening of the user interface.

An advantage of the mobile system is the capabilities of providing a prototype for a conference. As a consequence of this decision, a previously specified depth limitation of 300 mm will no longer apply. Resulting in a design in which the piping system is redesigned more compact and results in a more stabilizing system. Unfortunately, it also introduces the challenge of temporally connecting the system with the rigid sewage pipes. Flexibility in the connection is important due to the fact that most piping systems are installed with a 2 degree decline to ensure proper water flow and prevent odorous situations.

Additionally, accommodating different heights for the connection to the drainage system does need to be taken into consideration. several options are available to address the height variations in sewage pipes. One approach involves using flexible bending components with a rigid central piece, mimicking the human arms anatomy, with the elbow, wrist and bones. These flexibility makes the system be able to be concentric installed at a variety of heights. The flexible pieces are also proving a great option to connect the system temporarily due to the flexible parts being fastened with a hose clamp. Another solution is to incorporate rigid bend pieces and a telescopic pipe to adjust the height of the bend.

Fig. 13. The final prototype located in front of one of the Miele washer-disinfection machines. In the prototype, green indicates the pump, blue indicates the valves, red indicates the heat exchanger.

However, this will result in a problem of secure the system temporarily to the sewage piping. This can be achieved by adding a flexible straight end piece. The flexible bends are preferred due to their larger degree of freedom. For a detailed final design of the concept, refer to figure 10 and figure 13. To minimize the energy loss of the surface of the tank due to radiation, PIR plates should be installed to surround the tank to lower the emisivity and the surface temperature.

Discussion of simulation

The Heat exchanger has been designed using Solidworks, enabling the execution of computational tests. For simulation purposes, the initial temperature of the hot water is set at 60 °Celsius, as this temperature accounts for 60% of the effluent. Although 90 °Celsius effluent contains higher thermal energy, it only contributes to 20 % of the total effluent. Consequently, focusing on the equilibrium point at 60 °Celsius, 60% of the effluent, is sufficient to address the minimal efficiency increase of the system.

The initial temperature of the cold water is simulated at 15 °Celsius. Within the cleaning facility three Miele washing machines are installed, all intended to operate simultaneously. There may be instances where less washing machines are operational, therefor a limited cold water flow can be of interest in achieving a higher performance. It is important to note that the constrained cold water flow velocity should not pose any issues for meeting the water need of the external boiler and the washing machines. Notably, it becomes evident that when the cold water flow rate is lower, more energy is extracted into the cold water compared with a higher flow rate. Both cold water flow simulations shows an optimum around 40 liters per minute of hot fluid flow.

As 66% of the dirty water is recirculated within the system, the average temperature at the HEX inlet gradually decreases. With a flow rate of 35 liters per minute and a constant water volume in the tank, it is expected that all the water will cycle through the system approximately three times. However, due to hardware constraints, only the initial cycle, starting at 60 °Celsius, is simulated. This resulted in a temperature difference for the hot water at 60 °Celsius. The subsequent two cycles, with a lower temperature, are assumed to provide the same temperature difference but over a reduced temperature range.

In reality, the temperature gradient plays a significant role in the amount of energy transferred. To enhance the precision of the simulation, two additional simulations could be conducted, each using the outlet temperature after the previous water cycle through the system. A lower initial inlet temperature leads to a reduced energy transfer, consequently a smaller temperature decline in the hot water. This process should be performed a third time to obtain a more accurate outcome.

Discussion of experiment

The requirements setup in the method phase considered an energy decrease of 25 % of the external boiler. The results of the experiment showcases an decrease of energy need between 32% and 63%. During testing there was no blockage in the flow noticed at any time. The pump's power consumption was measured at 20 Watts. Considering the pump operates for 10 minutes per washing program (four cycles of 2.5 minutes each), the additional electrical energy consumption is just 0.03 kW. This minimal energy usage is uninteresting in regards to the overall energy savings achieved.

One notable challenge encountered during the experiment was achieving the target water temperature of 60 °Celsius simultaneously with the specified volume needed. At times, the water temperature reached 58 °Celsius, even though the 70-liter volume mark had been reached. To address this, extra hot water was introduced to reach the desired 60 °Celsius. This adjustment slightly increased in overall thermal energy. To take this into account, the efficiency contributing to 35 liters of hot water and 45 liters of hot water was calculated.

The total heat transferred between the cold and hot fluids is larger then expected. During testing, it became evident that the washing machines were consistently in operation during office hours, extending up to 18:00 hours. This operational schedule led to a lower cold water mass flow rate than initially simulated.

In table 8, the test averages are presented, combining the results from the 35-liter and 70-liter tests, the overall test average and the initial hypothesis. Notably, the temperature difference (Δ T_Clean_in and T_Clean_out) is larger than simulated. This can be caused by the limited water flow available during testing. The only source of cold water tap available to connect a hose to was located just before the external boiler's inlet. Throughout all the tests, the operational washing machines extracting heated water from the external boiler, influenced the flow velocity, resulting in an average between 8-12 liters per minute due to the external boiler's water extraction.

Additionally, it can be noted that a relatively high average T_Clean_in temperature, originating from the cold water source directly from the tap, which measured at almost 25 °Celsius on average. Instead of the anticipated, rule of thumb, 15 °Celsius. This temperature difference could be caused by factors like heat radiation from the tanks surface and convection within the entire heat exchanger system. These factors may have contributed to the higher measured T_Clean_in temperature.

The difference in the energy transferred and efficiency calculation by the temperature difference of the mass of hot water and cold water is large (32%-42% for hot water calculation and 43%-63% for cold water calculation). The fact that the tests were conducted with a less then optimal circumstance resulted in man made inputs instead of machine made, the else stable factors were in-stable. One of this in-stable factor was the amount of hot water combined with the precise temperature not being consistent due to input method. The other in-stable factor, the cold water flow, was notably effected by the external boiler water request at specific intervals. Both the mass of the hot water and the flow rate of the cold water are majorly impacting the efficiency calculation. Due to the fact that the cold water flow is more prone to be influenced during the experiment. The calculations of the hot water heat transfer is more stable. Resulting in a more reliable efficiency calculations of the hot water and thus a total efficiency between 32% and 43%.

Conclusion

In conclusion, the development and successful testing of the mobile modular Reothermia system in a representative setting have yielded promising results. The system demonstrates the potential to recover up to 47% of energy from standard water input conditions.

The system efficiently recirculates hot effluent through the piping network and facilitates heat exchange in the STHEX, continuously discharging a portion of the recirculated dirty water into the sewage to provide an enmpty tank when enough cold water is heated. This process elevates the temperature of cold water passing through the Reothermia system to approximately 35 °Celsius.

Looking ahead, an important aspect to consider for future work is the installation of a bypass pipe for colder water in the pre-washing cycle. This adjustment dismissed the reduction in the temperature gradient and remains the energy transfer.

The modularity of the design showcases its versatility but also opens up opportunities for presenting the prototype at conferences, garnering attention to the innovative approach for reclaiming energy from effluent waste.

Practical implications of implementing this system include a potential reduction in power consumption of 2.3 kWh per washing machine, leading to an overall efficiency improvement of about 47% in external boiler energy use. This translates to substantial annual savings, 7,680 kW of energy, a reduction of 1,129 kg of CO2 emissions, and cost savings of approximately 3,000 euros. These figures, combined with a relatively short payback time compared to other sustainable technologies like solar panels, makes this Reothermia system an attractive and eco-friendly choice.

The final step involves integrating this energy-recovery system into the operational washing-disinfection sewage line by exploring one of the solutions presented. With these benefits in mind, it is clear that the Reothermia system has the potential to be a major opportunity for energy recovery from wastewater. Its successful integration into operational systems promises a sustainable and cost-effective future.

Future work

There is a straightforward design improvements that can be implemented in the tank's design, instead of bending the short edges, it's advisable to bend the long edges. This alteration will reduce the length that needs to be welded. Another aspect that could be improved is to redesign the tank so the tank has a single low exit point, where the water will flow through.

Another enhancement to consider is the addition of a bypass for the pre-washing cycle (30 °Celsius) within the system. When the washing machines do not start simultaneously, the cycles do not overlap, and this can lead to a cooling effect on the effluent of other cycles, ultimately reducing heat transfer efficiency.

The precision of the experiment can be improved by installing the system into the sewage line and a cold flow speed meter into the cold water pipes.

To integrate the heat exchange system into the washing-disinfection facility at GreenCycl, a vertical pumping system is necessary to discharge water into the heat exchange system's tank. Several solutions can be explored:

1) Replacing the solenoids in the washing machines with optional pumps.
2) Installing a small tank within the piping system that employs a similar principle, incorporating liquid sensors and a pump for transferring water into the heat exchanger tank.
3) Exploring a creative approach of digging a hole and submerging the heat exchanger system into it, eliminating the need for a significant height difference.

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NOMENCLATURE

.

q= Heat transfer rate [w]
h= Heat transfer coefficient[w/m^{2}k]
A= Surface area [m^2]
T_s= Temperature of solid [K]
T_f= Temperature of fluid [K]
e = Emissivity [-]
T_R = Temperature of the room [K]
T_O = Temperature of the object [K]
T= Temperature [K]
σ = Stefan-Boltzmann constants = 5.670 x 10^-8 [Wm^-2 K^-4]
dm= Thickness of material [m]
Nu= Nusselt number [-]
Pr= Prandtl number [-]
Re= Reynolds number [-]
R= resistivity [K/w]
r= Radius [m]
L= Length of an object [m]
κ= Material conductivity [W/mk]
f= Friction factor [-]

P= Pressure [N/m^2]
v = flow speed[m/s]
t= time [s]
f= Body forces [N]
τ = Deviatoric stress tensor[-]

Dirty water: if the term dirty is used the effluent flow of the washing machine is described.
Clean water: If the term clean is used tab water is described.
STHEX : Shell tube heat exchanger
HEX: Heat exchanger
PHEX :Plate heat exchanger
HCHEX: Helical coil heat exchanger
PP: Polypropylene

APPENDIX A: GREENCYCL INTRODUCTION

GreenCycl is founded in 2019 by Joost van der Sijp, Majid El Mortadi, Bart van Straten and Tim Horeman and with support from CSA services. Their first major focusing point was to investigate and provide the possibilities to reuse face masks during the Covid pandemic by sterilization. GreenCycl is a company located in De Meern near Utrecht. The focus of the company can be described as:

A future in which medical instruments remain in use for as long as possible, and are then recycled or reused at the end of their life cycle. In this way, we can change the supply chain from 'take-make-use-dispose' to 'take-make-use-reuse'. [5]

The specialization of the company can be summarized into four separate services. The first service they provide is the laboratory service in which they provide the possibility for particle measurement, material specification, quality of waste for recycling, CSA testing and corrosion tests. These test are all done in the modern labs of GreenCycl. The second service that GreenCycl provides is the consulting in which they work out business cases. Implementation of circularity and decreasing of instruments number is one of the main focused points in these cases. GreenCycl will calculate the decrease of CO_2 emission, decrease in the energy and water consumption's and the savings in operational costs.

The third services which GreenCycl provide is the implementation of circularity and thus savings in the likes of: rental of instruments, sterilization of instrumentation and the collection and recycling of medical waste. The last service GreenCycl provide is the possibilities to make designs for sustainable and circular products. GreenCycl started with the melting of blue wrap polypropylene(PP) paper that is used to wrap instruments basket after sterilization. This single use material used to be be incinerated after single use. GreenCycl did research in their lab to make sure that if the blue wrap is disinfected according to a specific method the blue wrap can be melted into blocks and be used for injection moulding. For the injection moulding they work together with a company in Den Haag. This injection moulding company in collaboration with researchers of the TU Delft and the lab employees of GreenCycl have designed the GO jack, see figure 14, the function of this piece is to keep scissoring instruments open to improve the cleaning. The GO jack is shipped and sold all over the world.

Fig. 14. GO JACK is the end product of a design line started from the intake of blue wrap polypropylene paper, disinfection, melting, prototyping, testing, injection moulding and shipping worldwide. [6]

Appendix: B Analyse of the current situation/ problem definition

Situation sketch

The study is conducted in the living lab of GreenCycl, with three Miele PG 8528 washer disinfection machines see figure 14. These machines at Greencycl are installed on a platform providing approximately 23 cm clearing underneath and 70 by 100 cm in horizontal space. This space is not common for commercially washing machine lines but is specially designed to make sure that all around the washing machine equipment can be installed or research can be conducted. The machines are spaced 48 cm from each other providing room for equipment or research. However above the machine is no space because the dryers of the machines are installed there. In the dirty side of the cleaning facility plenty of available space to install a heat exchanger and a temporary water storage is available. The power, hot and cold water tap source are conveniently located between all the machines at a height of approximately 200 cm. The external boiler, a Daalderop MONO-3 (Koper type 07.11.49.254 150L), is located in the hallway, about 5 meters of the middle washer and disinfection machine. The external boiler provide the washing machines with hot water at a temperature of 70 °Celsius. The drainage pipes of the washing machines are connected to a pipe of 50 mm diameter and is situated around the inside walls of the dirty room, this provides good access anywhere to the drainage if needed.

Water consumption chart method

A field research is conducted to gather preliminary insight into the machines water temperature, naming and operational timing. In this field research an internal thermometer, internal clock and an independent timer were employed as measurement tools. Although the water temperature cannot yet be measured, the chamber temperature, displayed on the machines dashboard, is assumed to be the temperature of the water. Conducting research on the water flow pathway is crucial to locate potential in and outlets for a heat exchanger. The knowledge derived from the initial field test serves to make educated guesses about the capacity and parameters of a future HEX.

The timing protocol for the emptying of the machine started when the sprayers stopped spraying completely and the timer stopped when initial presence of clean water is detected. Typically, this initial water is first observed at the bottom half of the machine, spraying out of the lowest spraying arm into the water reservoir. The timer for the filling phase will be started at this point, when all the spraying arms are in a regular rotating motion, the timer of the filling phase will be stopped. The washing and disinfection machines had a maintenance service where the total water consumption is checked, this is 35 liter per cycle. With a total of five cycles that requires water, the total usage of the program accumulate to 175 liter of water. The 5 cycles contribute to one total cleaning program which, according to the employees, takes between 69 minutes and 79 minutes.

Water consummation chart results

To gain insight in the water flow trajectory of the washing machine a field research need to be conducted. This is prerequisite for strategic incorporation of water inlets or outlets for both clean and dirty water. The operational program of the machines comprised of a diverse array of cycles, each cycle will serve a different purpose. The machine uses water to clean or disinfect the instruments. After completing each cycle the 35 liters of water used is discharged into the sewage at a flow of approximately 70 liters per minute.

The starting position of the water is highlighted in the top left corner of figure 16, where unheated water at approximately 13 degrees Celsius is tapped into the external boiler. In the external boiler, located in the hallway, the water is heated up to 70 degrees Celsius. This heated water will flow though the piping network to either the

TABLE 9. Overview of the timing and temperature of the different cycles of the washing-disinfection program.

Programme name	Filling time (sec)	Final temp(C)	Programme time (min)	Emptying time (sec)	Water usage (L)
Pre-washing	90	28	7	35	35
Rinsing	120	56	12	40	35
Neutralising	120	57	9	40	35
Washing II	120	58	7	35	35
Thermal desinfection II	150	93	19	60	35
Drying	AIR	112	15	AIR	AIR

Fig. 15. Depiction of the Miele washing-disinfection machines and the situation sketch of the dirty side of the GreenCycl washing and disinfection facility.

washing machines or to the kitchen sink. Notably, the temperature of the hot water inlet of the washing machine can vary between 20 degrees Celsius and 70 degrees Celsius. This temperature acceptance opens up to direct the preheated clean water from the HEX directly into the washing machines. An internal boiler is also installed in the washing machines to recover dissipated energy due to radiation, convection and conduction to the environment. Small volumes of cold water is added throughout the whole program.

In the initial cycle, termed by the machine as ”pre-washing”, the chamber temperature of the washing machine will be heated up to 30 degrees Celsius and will be emptied after 7 minutes of continuous spraying. During the ”cleaning” cycle the water is heated up to 56 degrees Celsius and is being sprayed over the instruments for 12 minutes. After this cycle is complete, the hot water in the washing machine is being emptied into the sewage again. In the cycle termed by the machine as ”neutralising ” the spraying water is being heated up to 57 degrees celcius and cleans the instruments for 9 minutes before the dirty water is drained in the sewage again. The next cycle is termed as ”spoelen II” the water is heated up to 58 degrees Celcius and is washing the instruments for 9 minutes. Once these cycles are finished the ”des thermisch II” will initiate. This is a crucial cycle to kill all the bacteria and viruses and makes the instruments safe to handle, in adherence to the regulations outlined in ISO 15883 [7]. These regulations stipulate that the washing cycle responsible for the disinfection will heat up the instruments to 94 degrees Celsius for at least one minute [8]. After the ”des thermisch II” the content of the machines will undergo a hot air drying process, labeled as ”drying”, thus concluding the total cleaning program.

The comprehensive water consumption throughout a complete washing program is 175 liters. Of this, 105 liters of water is used at 60 degrees Celsius, 35 liter at 94 degrees Celsius and the remaining 35 liter at 30

degrees Celsius for an overview, see figure 17 and table 9.

Water flow path

In the present configuration, the machine's hot water discharge after every cycle (35 liters) is directly drained into the sewage system. To enhance the possibility to install a heat exchanger for optimized heat exchange, a temporary storage tank is needed. Given the machine's high flow rate of approximately 70 liters per minute for 30 seconds, the application of a heat exchanger is limited. Introducing temporary hot water storage increases the heat exchange applications and might result in better heat exchange results. To facilitate data collection about the energy consumption of the external boiler and the washing machines a kWh meter within the power grid is contemplated. Moreover, the placement thermometers within the water pipes is needed to enable a continuous monitoring of water temperature at specific points.

Initial power consummation gathering

To initiate the process, first initial data need to be gathered, which will serve as a basis for comparing the outcome of the project with the current scenario. The decision is made to integrate the heated output of the clean water heat exchanger directly into the water input of the external boiler. This means that the temperature of the water is increased in the new situation. Consequently, there is reduced energy demands to heat all the water to the used 70 degrees Celsius. The performance of the HEX can therefor be showed as the diminished electrical energy required for heating the water. To facilitate tracking of the electrical consummation, a kWh meter is installed into the grid of the external boiler.

To track the electrical consummation of the external boiler an ORNO-OR-WE-516 kWh meter is selected and positioned into the power grid of the external boiler. This power meter featuring compatibility with an RS485 and Modbus interference, these features can provide a data connection with Arduino. The boiler will supply the washing machines and the sink in the kitchen of hot water. Notably, the consummation of hot water of the sink in the kitchen is considerable lower in regards to the water consummation of the washing machines. The large difference in consummation means that it is assumed that the allocated energy consumed by the boiler to heat up the water is either allocated to the water consummation of the washing machine or dissipated as radiation on the surface of the external boiler.

The policy of the company states that every time the machines are in operation the contents need to be weighed and documented. Although the weight of the content that is washed is not of any influence on the power consummation of the external boiler, it does influence the energy consummation of the washing machines. The heat absorbed by the colder instruments due to conduction of hot water is reheated by its internal boiler.

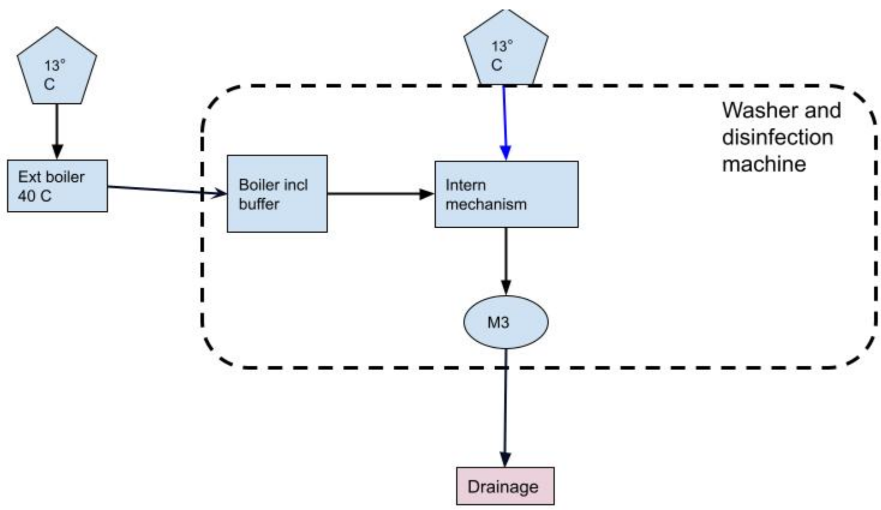

Fig. 16. Route 1 illustrates the initial water flow of the washing-disinfection machine, in which the effluent will be directly drained into the sewage.

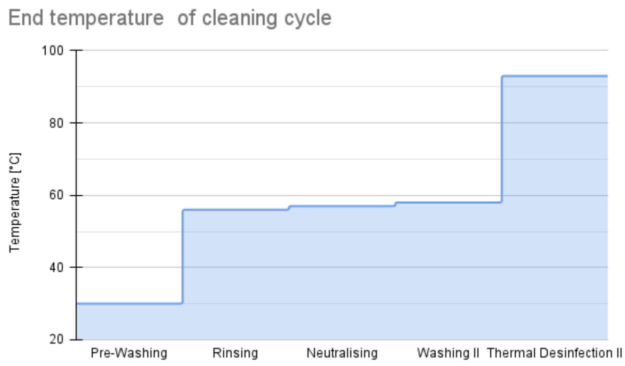

Fig. 17. The temperatures of the different cleaning cycles are depicted into the graph. Each cycle contains 35 liters of water.

The experimental framework should consist of the energy meter providing a 24/7 data measurement. The ORNO-OR-WE-516 is specifically selected due to the capability to be connected to an Arduino and enable usable data provided by the power meter. This data in combination with the documentation of the employees about the washing operation and the time schedule should provide the information to determine the average power consummation of the external boiler.

Initial attempts at executing the experiment included incorporation the Modbus to connect with the Arduino. Unfortunately, after 2 weeks of continues trial and error, help from the supervisor and help from a software engineer, the code still did not work and consequently an alternative experiment needs to be charted.

To still gain knowledge about the energy consummation of the external boiler another small experiment is charted. This entails documenting the kWh meter value by hand, written down prior a single washing program and proceed to wash an entire program and once the machine is finished the kWh value will be written down again. The discrepancy between these values directly signifies the overall kW consumption of the external boiler for heating hot water. This experiment will be done eight times in total between 26the of May when the power meter was integrated and the 13the of June. The results of the experiment can be seen in figure 18.

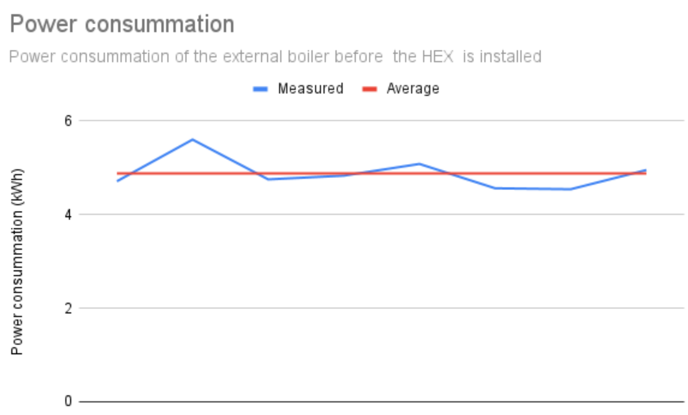

Fig. 18. External boiler energy consummation, in absence of a heat exchanger, charted per complete washing and disinfection program per washing machine.

The average power consummation of the external boiler, in the absence of a heat exchanger, for each washing cycle per washing machine is established at 4.86 kW.

If the three machines are operational 20 times per week. Which accounts to 3000 times a year in fully operational conditions. According to the research done by Sims et all [2003] [9] 147 g of CO2 is produced per kW energy that is produced in a gas powered energy plant. The year round consumation of energy contributes to a total of 14 500 kg of CO2 per year. The energy price per kWh is about 40 cents and is guessed not to drop drastically in the next few years [10]. The overall operational cost of the system could be 5800 euros per year.

APPENDIX C: LIST OF REQUIREMENT

TABLE 10. LIST OF REQUIREMENTS WITH PASSING CRITIRIA

Requirements	Passing criteria
Decrease the energy usage of the external boiler by 25% due to an increasing temperature of the water inlet.	Decrease power consumption of the external boiler by 25 %
To ensure good working of the washing machine, the water flow should not be blocked nor a leakage should occur.	No leakage or blockage of flow should occur in the heat exchange system.
The system should enhance CSSD employee safety by providing clean and safe work environment, for example, no sharp edges/parts.	No sharp edges/parts and provide warning sign.
The design should meet the required standards and regulations.	The device should meet the requirements and standarts for safe use.
The HEX system has no influence on the operation of the washing and disinfection machine itself.	The effluent should always be able to flow.
The system should not exceed a depth of 300 mm to minimize interaction with the working area of the employees in the cleaning and disinfection facility.	The system should not exceed a depth of 300 mm.
Every part should be accessible within 5 minutes of disassembly for maintenance or repair purpose.	Each part should be accessible within 5 minutes.
Durable and corrosion-resistant material to withstand repetitive use and temperatures of 100 °Celsius (Boiling point .)	Use PP piping and stainless steel parts.
The design (expect frame and tank) should be easily adaptable (temporary fixations) to contemplate future improvements and research.	Use of connections without need for (power) tools .

The SMART methodology to describe the requirements of the design is showed below with an explanation.

Requirement: Decrease the energy usage of the external boiler by 25% due to an increasing temperature of the water inlet.
S=Cold water is currently heated in the external boiler prior to entering the washing machines. The cold water can be preheated in the heat re-winning system.
M= Measure energy usage of the external boiler by the newly integrated power meter.
A= Maximum theoretical efficiency of the heat exchanger is established at 43%.
R= The dutch government strives to a zero emission healthcare in 2050.
T= This requirement should be reached at the end of the project.

Requirement: To ensure good working of the washing machine, the water flow should not be blocked nor a leakage should occur.
S= To conclude a continuous working progress, the effluent of the washing machines should not be interrupted or delayed to exclude errors.
M= Check if water is leaking somewhere and test the through flow of all the components.
A= To ensure no leaking or blockage, it is preferred to only use PP parts for the water ways.
R= Water escaping the system could damage the surrounding equipment.
T= During testing and operation, no leakage or blockage should occur.

Requirement: The system should enhance CSSD employee safety by providing clean and safe work environment, for example, no sharp edges/parts.
S= The projected placement of the washing machines is at the dirty side of the cleaning room. The employees wear protective equipment, which absolutely cannot be damaged by sharp parts.
M= Follow the contours of the prototype to determine the amount of sharp edges.
A= Include finish techniques for welds and use of end caps for pipes.
R= The prototype could be used in the dirty side of the washing facility.
T= At all time, there should be no sharp edges.

Requirement: Every part should be accessible within 5 minutes of disassembly for maintenance or repair purpose.
S= The placement of the heat exchanger is in a crucial position for a continuous operation of the washing machines. If a part is malfunctioning, this part should be able to be replaced rapidly.
M= The time span could be measured with assembling and disassembling the prototype.
A= With a limited amount and distinguishable parts that press fit the requirement can be achieved.
R= This design should be fast maintained or repaired. If the system is broken, the whole washing disinfection line is nonoperational.

T= During the total operation time.

Requirement: Durable and corrosion-resistant material to withstand repetitive use and temperatures of 103 °Celsius (sf=1.1).
S= The washing disinfection machines are discharging their effluent a total of 100 times a day with a maximum temperature of 93 °Celsius.
M= Check the temperature limit of all parts.
A= Use of PP parts and stainless steel 304 or 316 and components able to withstand the high heat.
R= Choosing the right material can enhance the life span of the device.
T=Check the capabilities of materials during the design process.

Requirement: The design should meet the required standards and regulations. S= To ensure save operation of the prototype itself and it's surrounding, a medical device regulation check should be conducted, or else checked which regulations are needed.
M= Check with help of the MDR if the prototype is a medical device. If not, if other standards should be met.
A= With help of the MDR and other regulations as needed.
R= To ensure save operation and follow the regulations.
T= During the design process.

Requirement: The HEX system has no influence on the operation of the washing and disinfection machine itself.
S= The only way the prototype could influence the operation of the washing and disinfection machine itself is if the water flow, both clean and dirty is not working properly. M= Test if the operation time remains the same.
A= The tanks should be able to store the effluent of the three washing machines simultaneously. The inflow into the tank should be of equal size of the drainage existing.
R= To ensure a continuous operation of the washing machines and the external boiler. And minimize the chance of errors occurring.
T= The requirement should be achieved during the whole operation time of the device.

Requirement: The system should not exceed a depth of 300 mm to minimize interaction with the working area of the employees in the cleaning and disinfection facility.
S= Do not exceed a depth of 300 mm, this is the depth at which the first washing machine is installed at the projected placement. If the prototype exceeds this depth it could influence the working flow for loading of the machines.
M= Check within solid works, during design, the depth of the prototype. Check afterwards with placement in the dirty room.
A= Make shore the design does not exceed 300 mm.
R= Not interrupting the working flow of the loading of the machines.
T= During the design process.

Requirement: The design (expect frame and tank) should be easily adaptable (temporary fixations) to contemplate future improvements and research.
S= This prototype is the first generations. Meaning that improvements are naturally to follow. To ensure implementation of new parts are easy, temporary connections are selected.
M= Do not use any power tools to connect something.
A= With help of temporary connections like hose clamps, press fit or threats.
R= To ensure future improvements and adaptations.
T= During the design process and Assembly phase.

APPENDIX D: PROPOSED HEAT EXCHANGE LOCATION

There are various possibilities for integrating the heated water from the HEX into the system. These options include utilizing the heated clean water for room heating, directly piping the heated water into the washing machine's hot water tap or connecting the heated water into the cold water inlet of the external boiler. The initial washing machine route is depicted in figure 16. Here, cold water is preheated to 70 degreess Celsius by an external boiler. Once the washing machine is activated, this water in combination with cold water will be used inside the washer- disinfection machine, reaching temperatures between 60 and 95 degreess Celsius, depending on the cycle. The water used for the cycle will be drained into the sewage. For a comprehensive view of the washing program cycles, chamber temperatures, and cycle names, refer to figure 17 and table 9. All implemented heat exchangers routes will incorporate a temporary drain storage to handle the discharge of 35 liters of water per machine at a rate of 70 liters per minute. The heat exchanger maintains separation between the hot and cold fluids, storing the hot fluid in the temporary storage (shell side) while the cold fluid flows through the tube side of the heat exchangers. This configuration allows the cold tube side to be heated and the shell side fluid to be cooled. If the shell side is empty, the temperature of the water in the tube remains unaffected.

Route 2, illustrated in figure 19, involves modifying the external boiler's water inlet to redirect it through the HEX the effluent of the washing machines will provide the thermal energy for the HEX. This preheats cold water destined for the external boiler. In the initial cycle, containing no hot water in the water tank, the boiler's water flows through the empty HEX system without losing or gaining thermal energy.

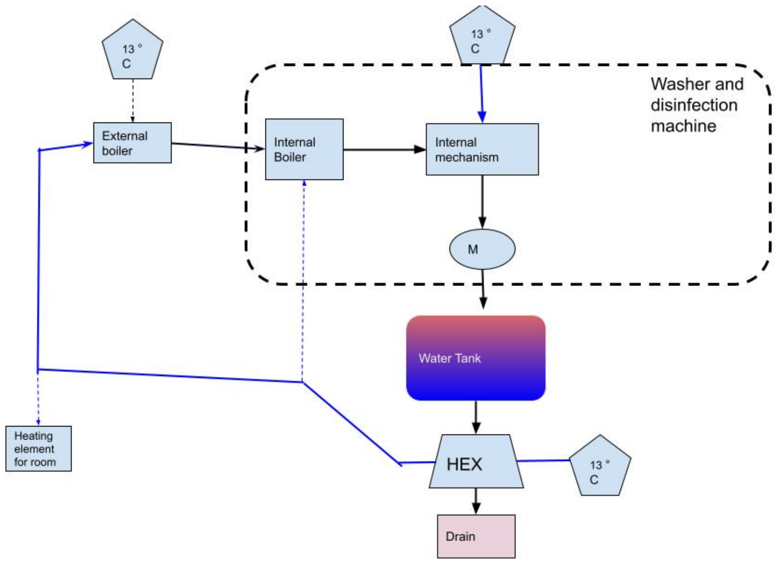

Fig. 19. Route 2 illustrates the cold water flow being heated by the HEX and integrated into the external boilers cold water inlet.

Route 3, as depicted in figure 20, proposes a solution for room heating. Considering the significant heat generated by the washing machines themselves, the installation area might not require an additional heat source under normal weather conditions. The office located above the cleaning facility also does not need heating for most of the year. However, while this approach might be suitable for colder climates, it is not applicable to this situation.

Route 4, shown in figure 21, involves utilizing the external boiler for the "pre-washing" and "rinsing" cycles to supply heated water to the washing machine, even though the water will flow through the heat exchanger the shell side is either empty or about 30 degrees Celsius. Whilst for the other cycles, the clean water will be heated by using the hot water from the heat exchange shell side. A valve opens to allow clean heated water to flow to the tap of the internal boiler of the washing machine. The machine's internal boiler further heats this water for the following phase. However, precise software and hardware regulation are crucial for managing the correct water flow through these components.

Among these options, route 2 (figure 19) emerges as the preferred choice. The external boiler can handle "cold water" temperatures up to a maximum of 70 degreess Celsius, which aligns with the hot water inlet temperature

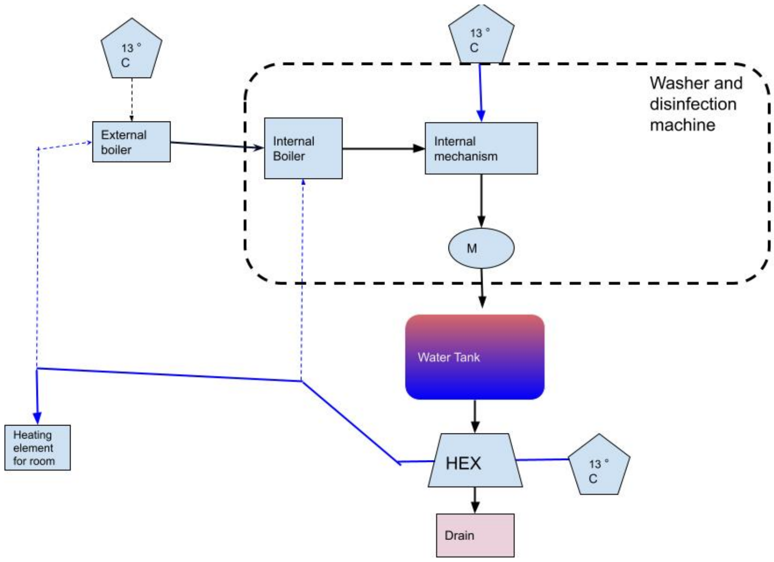

Fig. 20. Route 3 illustrates the cold water flow being heated by the HEX and integrated into an external heating element for heating of the room.

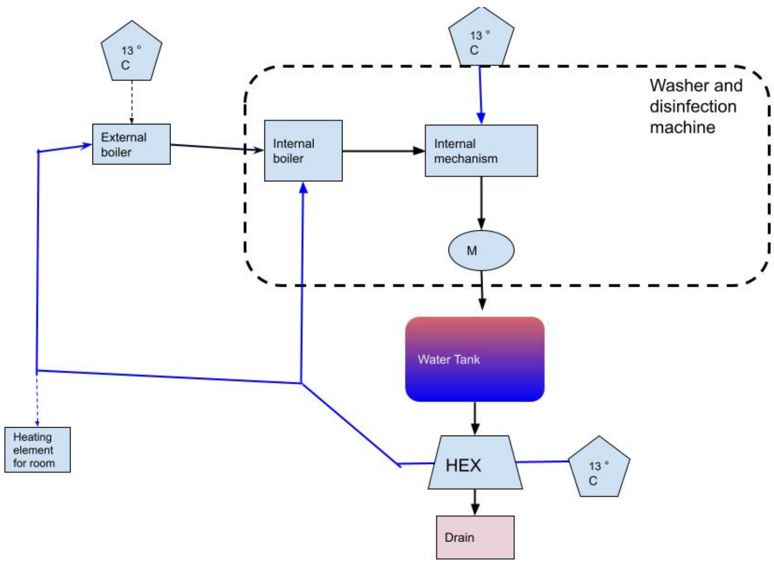

Fig. 21. Route 4 illustrates the cold water flow either flowing through a cold hex into the external boiler or a cold water flow being heated by the HEX and integrated into the internal boiler of the washer and disinfection machine, regulated with software.

limit of the machine's internal boiler. This approach offers the advantage of requiring no adjustments inside the machine. The primary focus aiming to the results of this study is to analyze the power consumption of the external boiler, aiming to achieve reduced energy consumption through a higher cold water inlet temperature.

APPENDIX E: TYPES OF HEAT EXCHANGER AND THEIR COMPARISON

There are three main types of heat exchangers:

- Direct contact
- Regenarotor
- Recuperator

Direct contact heat exchangers are typically used in very large volumetric mediums such as cooling towers and power plants. In direct contact heat exchangers, the cool fluid and the hot fluid are mixed because there is no wall (tube) to separate the fluids from mixing with each other. This is not a suitable kind of heat exchanger to be used for this application. The regenerator is a kind of heat exchanger that can be found inside a refrigerator. In regenerators the hot fluid will exchange the heat to a medium. Before this medium is being rotated to exchange its heat to the cold water. Minor mixing can occur in this kind of heat exchangers, therefore a regenerator is not a suitable option for this design.
The recuperator is a heat exchanger which separates the heat by a wall. There is no mixing of the fluids possible resulting in no possible cross contamination in the heat exchange process. The heat will be exchanged by solely convection and conduction throughout the mediums and the walls.

Firstly the different kind of recuperator heat exchanger will be compared. Their advantage and disadvantages will be discussed as well as the types of flow. Tools to calculate the different kind of Heat exchangers will be explored.

Helical Coil heat exchanger

Helical coil heat exchange (HCHEX) are commonly employed in large scale factories with its main function to heat or cool a large quantity of liquid. A tank is filled with a hot fluid and a coil with cool fluid will exchange its heat with the fluid in the tank. An implementation of the system is depicted in figure 22. With the shell of the heat exchanger being filled with the hot water of the machine and emptied into the drain after a determined period of time. A helical coil tube heat exchanger is build up from a tube which is bend into a helical shape. This helical shape will provide a secondary flow, caused by the centrifugal forces, this secondary flow has major positive effect on the mixing of the fluid in the tubes. The mixing of the fluid inside the tube is especially beneficial for laminar flow. Fouling of heat exchangers is the build up of materials like: bacteria, salts, residues, fungous et cetera on the wall of the heat exchanger. Heat exchangers that are not treated will decrease in efficiency due to fouling. This fouling can be decreased with help of a PWT coil and a filter. The amount of fouling can also be limited due to certain design choices. More fouling will occur when the flow is more turbulent thus can be characteristic by a high Reynolds number Re$\geq$ 4000. A common tool to design a helical coil heat exchanger is by using specific programs such as Comsol or Solidworks. In these programs a design can be made and a heat transfer simulations can be conducted to gain knowledge about the total heat transfer. Advantages and disadvantages are listed in table 11.

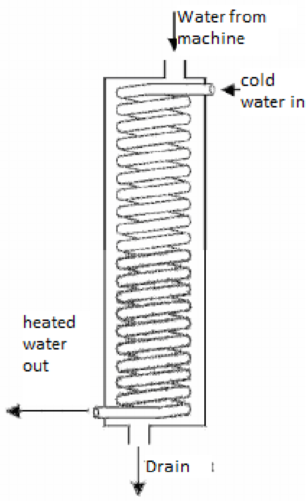

Fig. 22. Schematic working mechanism of a helical coil heat exchanger implementation at GreenCycl cleaning and disinfection facility [11].

TABLE 11. ADVANTAGES AND DISADVANTAGES OF A HELICAL COIL HEAT EXCHANGER.

Advantage	Disadvantage
No need to have a continuous flow of the hot fluid	Not the most efficient heat exchange mechanism
Easy to manufacture	No counter flow possible
Easy to clean	Difficult to clean
Secondary flow in tubes	High pressure drop
Durable design	

Plate heat exchanger

Plate heat exchanger or plate-and-frame heat exchangers are adjacent plates which are soldered, welded or brazed together or tightened together with help of nuts and bolts. These adjacent plates have a corrugation which results in an even divergence of the medium over all the plates. Corrugation in the plates are build up in a pattern called chevron angles, these angels will force the flow of the medium to diverge, this diversion will increase the total turbulence of the system. The most important parameters influencing the efficiency of the plate heat exchanger are chevron angles of the corrugation and surface roughness of the plates. Fouling of a heat exchanger is the build up of materials like: bacteria, salts, residues, fungous etc. on the walls of the heat exchanger. Heat exchangers that are not treated will decrease in efficiency due to fouling. This fouling can be decreased with help of a filter. The amount of fouling can also be limited due to certain design choices. A common design tool is the Wilson plot to get knowledge about the optimal parameters. Unfortunately, empirical data is needed as an input to get a Wilson plot. Therefore heat transfer simulations of 2D or 3D models are used regularly. Counter flow between the hot and cold medium is the more efficient in heat transfer then parallel flow. Advantages and disadvantages are listed in table 12.

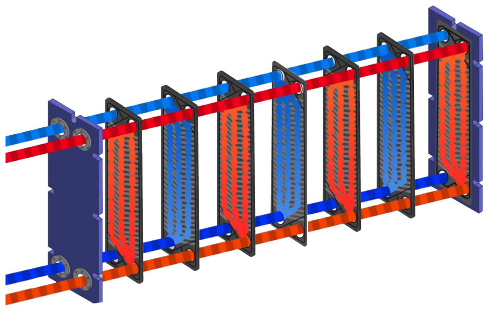

Fig. 23. Schematic working mechanism of a plate heat exchanger [12]

TABLE 12. ADVANTAGES AND DISADVANTAGES OF A PLATE HEAT EXCHANGER.

Advantage	Disadvantage
Efficient heat transfer over low temperature difference	Difficult to clean
Compact design	Need a continuous flow of hot fluid
Ease to extend	Expensive
	Prone to blockage

Tube and Shell heat exchanger

A shell-tube heat exchanger (STHEX) is contains 3 main parts, the tubes, the shell and baffles. The shell will provide a basin for the hot water to flow through. The baffles will support the tubes in the shell, the baffles are interacting with the water flow in the shell and provide turbulence. The tubes provide a pathway and barrier for the cold water to exchange the thermal energy in the shell. The baffles dimensions will have a big influence on the efficiency of the shell and tube heat exchanger. The baffle distance will also influence the amount of fouling occurring in the shell, an optimal distance need to be found to minimize the amount of fouling. To get insight in the total heat transfer of a STHEX, empirical data is commonly used. The Bell-Delaware method is very accurate at guessing heat transfer coefficient and pressure drop but needs empirical input. For the design of a STHEX the Kern method can be implemented, this method does not require empirical input but concludes only rough results. If no empirical data is available, heat transfer simulations of 2D or 3D models are also used. The direction of the water flow will play an important role in the amount of heat transfer in the system. The most efficient flow direction is the counter flow

TABLE 13. ADVANTAGES AND DISADVANTAGES OF A TUBE AND SHELL HEAT EXCHANGER.

Advantage	**Disadvantage**
Efficient heat transfer	Difficult to clean
Most common used for Liquid-liquid heat transfer	Need a continuous flow of hot fluid
Large amount of iterations possible in the design	High pressure drop

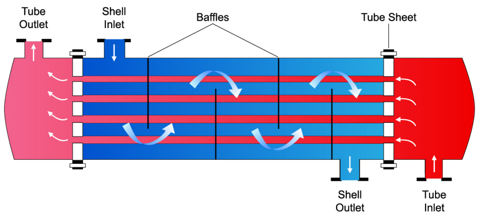

Fig. 24. Schematic working mechanism of a shell and tube heat exchanger. [13]

in which the temperatures gradient between the cold and hot water need to be as high as possible. Advantages and disadvantages are listed in table 13.

APPENDIX F:THEORETICAL BACKGROUND OF FLUID FLOW

In this study, a key factor contribution to the success lies in acquiring knowledge about parameters that influence the performance of a heat exchange system. Therefore, some general information about important fundamentals of fluid dynamics are depicted. To get knowledge about the fluid flow properties the equation of Navier-Stokes is utilized. Navier-Stokes equation is the basis for almost every fluid flow simulation that is done and is therefore deemed important to understand. The Navier-Stokes equation, depicted in equation 1, serves as a framework of describing fluid motion while the Mass-Continuity equation, see equation 2, addresses the conservation of mass.

Breaking down equation 1, the first term on the left states the change of velocity over time and is called the inertial force term. The second term shows changes in convection of the mass. The first term on the right side of the equation states hydro-static effects in the form of a pressure gradient. The second term denotes the viscous forces, the third term encapsulates the effects of compressability of the flow. The last term incorporates external body forces such as gravity.

$$\rho(\frac{\delta \mathbf{v}}{\delta t}) + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \ \nabla \cdot \tau + (\lambda + \eta)\nabla(\nabla \cdot \mathbf{v}) + \mathbf{f}(1)$$

$$\rho(\delta \rho / \delta t) + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{2}$$

Solving the equation of Navier-Stokes, equation 1, cannot be done analytically, due to the presence of the non-linear terms such as the advection term and the underlying interactions between certain variables. The non-linear term of the equation gives insight in the amount of turbulence in the system. Turbulence is the chaotic behaviour of a flow due to the internal acceleration, pressure difference and convection in time and space. For the application of designing a heat exchanger the equation is simplified. It is assumed that the advection is relative small compared to the others terms in the equation therefore decided to exclude this non-linear term out of the equation. It is assumed that the flow is in all-time steady state, resulting in all the time-variant parts of the formula equal to zero. This steady-state flow assumption will eliminate the first term on the left side of the Navier-stokes equation it also eliminate the first term of the mass-continuity equation. Both assumptions results in equation 4 in combination with the fact that ρ is not equal to zero. It is assumed that the fluid is in-compressible, this in-compressible term will results in the τ to be expressed in equation 3.

$$\tau = \mu(\nabla \mathbf{v} + \nabla \mathbf{v}^T)(3)$$

$$\nabla \cdot \mathbf{v} = \mathbf{0} \tag{4}$$

The equations 1, 2, 3, 4 are combined in a new simplified formula equation 5, this can be rewritten to equation 7.

$$\nabla p = \mu \nabla \cdot (\nabla \mathbf{v} + (\nabla \mathbf{v})^T) + \mathbf{f} \tag{5}$$

$$\nabla p = \mu \nabla \cdot (\nabla \mathbf{v} + (\nabla \cdot \mathbf{v})) + \mathbf{f} \tag{6}$$

$$\nabla p = \mu \nabla \cdot (\nabla \mathbf{v}) + \mathbf{f} = \mu \Delta \mathbf{v} + \mathbf{f} \tag{7}$$

The final formula derived from the Navier-Stokes equation depicted in (7), represents the pressure gradient (∇ p) in a fluid flow field.

∇ p: Represents the gradient of pressure in the fluid. It describes how the pressure changes across space or distance within the fluid.

μ: Represents the dynamic viscosity of the fluid. Dynamic viscosity measures the fluid's resistance to shear or deformation. It quantifies how ”thick” or ”sticky” the fluid is.

∇ v: This is the gradient of the fluid velocity vector (v). It represents how the velocity of the fluid changes across space.

$\nabla\cdot$ (∇ v): This is the divergence of the gradient of velocity. It describes how the velocity vectors spread out at a specific point in the fluid flow field.

F: Represents any external forces acting on the fluid, such as gravitational forces or other applied forces.

μ Δ v: This term represents the product of dynamic viscosity (μ) and the Laplacian of velocity (Δ v). The Laplacian of velocity is a measure of how the velocity field changes over space in a more complex manner than its gradient.

$\mu\nabla\cdot(\nabla$v): Represents the viscous forces causing pressure changes due to the fluid internal resistance to shear. This part is related to the fluid viscosity and how the fluid velocity changes.

Notably, the velocity parameter play an important role in the Navier-stokes equation. If the gradient of the velocity profile is larger more energy is transferred from kinematic energy to thermal energy. This loss in kinematic energy need to be reimbursed by an external pump and is called pressure loss.

APPENDIX G: THEORETICAL BACKGROUND OF HEAT TRANSFER

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Heat is a form of energy that naturally distribute from regions of high energy (temperature) to low energy, in accordance with the second law of thermodynamics.

Convection

Convection is the heat transfer within a certain fluid or gas. An increased convection rate leads to a quick equilibrium of temperature gradients within the fluid. Convection can occur spontaneously or be enhanced using devices like pumps or rotors. Newton's Law of Cooling, see equation 8, describes the convection of heat within a fluid.

$$q = hA(T_s - T_f) \tag{8}$$

The convection coefficient (h value) is greater for forced convection then for natural convection which is only driven by the temperature differences [14]. The flow field of a straight tube is different in regards to a flow field of a curved tube. The flow in the curved tube is causing a centrifugal force to enlarge the turbulence in a curved tube, increasing the convection rate [15]. The convection coefficient can be calculated by use of the Nusselt number.

Conduction

Thermal conduction describes heat transfer from a hot end of a solid object to a cold end of a solid objects like pipes. Conduction will only occurs in solid objects not in fluids or gasses. The ability of an object to conduct heat is known as thermal conductivity [κ]. A high thermal conductivity is resulting in a faster movement of the heat in the object. The heat flow of conduction can be described by Fourier's Law [14], see equation 9 .

$$q = -\kappa A \frac{\delta T}{dm} \tag{9}$$

Radiation

Radiation is the transfer of heat in form of electromagnetic radiation by a body due to its surface temperature [14]. All the Bodies with a temperature above 0 kelvin will emit radiation, there is no contact necessarily between different mediums to transfer the heat in radiation. This radiation equation can be described by the Stefan-Boltzmann formula, see equation 10.

$$q = \sigma Ae(T_R^4 - T_O^4) \tag{10}$$

The emissivity [e] is dependent on the material and color of the object, a black body has an emissivity of one. Notably, the absolute temperature of an object and the room is to the power of 4. Isolation of a heated object can drastically decrease the surface temperature thus decrease the energy dissipation.

q= Heat transfer rate [w]
h= Heat transfer coefficient[w/m^{2}k]
A= Surface area [m^2]
T_s= Temperature of solid [K]
T_f= Temperature of fluid [K]
e = Emissivity [-]
T_R = Temperature of the room [K]
T_O = Temperature of the object [K]
σ = Stefan-Boltzmann constants = 5.670 x 10^-8 [Wm^-2 K^-4]
dm= Thickness of material [m]

Heat exchange calculations

In a heat exchanger, the convergence of multiple heat transfer mechanisms are occuring simultaneously. In the heat exchanger the hot water flow through a pipe, the material of the colder pipe extract heat from the fluid due to conduction. The pipe transfer the heat by conduction to the cold medium in the shell of the heat exchanger.

One of the conditions stated is that the fluid must maintain its phase throughout the whole process. Additionally, throughout the whole process there is a constant contact that dictates the absence of radiation heat exchanges in the system. Consequently, a formula can be introduced that exclusively addresses convection and conduction within the heat transfer mechanism. When employing simulation software, these formulations serve as the bedrock for the simulation equations. These foundational equation are rewritten to be able to showcase the total heat transfer. These equation needs to be redefined into an equation with the resistance (R) factor in it. Equation 9 can be reformulated into a formula that explicitly is used to calculate the heat transfer in radial direction.

The culminating expression, presented in equation 15, shows that the only parameter that can be manipulated is the heat transfer coefficient (h). Notably, change of this coefficient is primarily dependent on the velocity of the flow. The (R) Resistance stated in equation 13 and equation 14 are instrumental to calculate the overall heat transfer. Figure 25 showcase the composite resistivity, functioning similar to series electrical resistance. The figure encapsulates heat transfer equations spanning over the cylinder area shown along with some of the parameters.

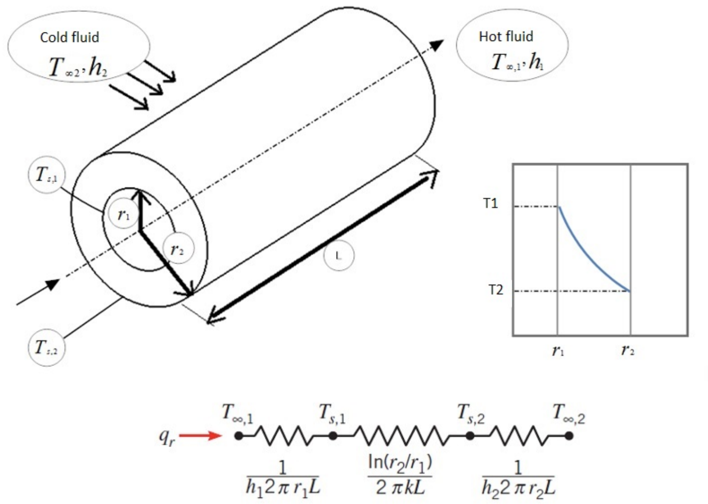

Fig. 25. Calculation of total resistivity of a single pipe in a heat exchanger [16].

The heat transfer coefficient (h) can be determined precisely with experiments or be educated guessed with help of a Wilson plot or with the implementation of the dimensionless numbers. These dimensionless numbers are helpful to determine the convective heat consisting of the Reynolds number, Nusselt number and Prandtl number. The inner radius(r_i) of the pipes of a heat exchanger is of influence on the Reynolds number. Adjusting the velocity of water flow velocity will result in a strategy to optimize heat exchanger efficiency.

$$\frac{q_r}{A_r} = -\kappa \frac{\delta T}{\delta r} \tag{11}$$

.

$$q = \frac{\Delta T}{\sum R} \tag{12}$$

$$R_{cyl} = \frac{ln(\frac{r_o}{r_i})}{2\pi k L} \tag{13}$$

$$R_{sc} = \frac{1}{h_o A} \tag{14}$$

$$q = \frac{\Delta T}{\sum R} = \frac{T_{ts} - T_i}{\frac{ln(\frac{r_o}{r_i})}{2\pi rkL} + \frac{1}{h_o 2\pi r_o L} + \frac{1}{h_i 2\pi r_i L}} \tag{15}$$

q= Heat transfer rate [w]
A= Surface area [m^2]
T= Temperature [K]
r= Radius [m]
L= Length of an object [m]
h= Heat transfer coefficient[w/m^{2}k]
κ= Material conductivity [W/mk]

Dimensionless numbers

Dimensionless numbers are very helpful to describe different aspects of the flow and heat transfer within a system. Important parameters used for different calculations of heat transfer enhancements and coefficients are listed below:

- **Nusselt number(Nu)** which is the ratio of convective heat transfer in regards with the conduction heat transfer. The Nusselt number can be described in numerous different ways.
- **Prandtl number(Pr)** compares thickness of the velocity boundary layer (momentum) with the thickness of thermal boundary layer .
- **Reynolds number(Re)** Reynolds number shows if the flow is laminar or the amount of turbulence in a flow.

The Nusselt number encompasses a range of dimensionless parameters discussed earlier. These parameters correlate with various coefficients established through experimental data for specific parameter values. Notably, not all parameters are used for Nusselt number calculations, allowing for a degree of simplification. A diversity of equations is available to calculate the Nusselt number, demonstrated across a number of sources [17-20], where a comprehensive collection of 53 equations to calculate the Nusselt number is shown. Within the scope of this paper, the Nusselt number is computed using both the Gnielinski formula and the Dittus-Boelter equation, presented as formula [16] and formula [17]. The Dittus-Boelter equation is mostly used for its simplicity and its widely adaptability. The Gnielinski formula, while more intricate, affords improved precision due to its capacity to handle complexities in heat transfer .

$$Nud = 1.045Re^{0.303} * Pr^{0.297} \tag{16}$$

$$Nug = \frac{(f/8) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot (f/8)^{0.5} \cdot (Pr^{2/3} - 1)}$$

(17)

$$Nu = h * Hd/\kappa \tag{18}$$

$$Re = \rho * v * Hd/\mu \tag{19}$$

$$Pr = \nu/\alpha \tag{20}$$

With ρ = Density of the fluid [kg/m^3]
v= Velocity of the fluid [m/s]
Hd= Hydraulic diameter[m]
μ = Viscosity of the fluid[kg/(ms)]
α = Thermal diffusion rate [m^2/s]
ν= Viscous diffusion rate [m^2/s]

κ= Material conductivity [W/mk]
f= Friction factor [-]
h= Heat transfer coefficient[w/m^{2}k]

APPENDIX H: HARRIS PROFILE

TABLE 14. CRITERIA EXPLANATION OF THE HARRIS PROFILE.

Criteria	Explanation
Adaptability	The Greencycl lab wishes to do further research and implement more efficient items into the setup. It is therefore important to make parts of the design, be easily adaptable or add equipment to the setup.
Controllable efficiency	A controllable system should haves the possibilities to be setup to exchange energy in an optimum which will maximize the performance of the heat exchanged.
Base efficiency	A standard high efficiency has the possibilities to exchange more heat in the total system, which will decrease the costs and energy needs to heat up the water in the external boiler.
Complexity	How much regulation is possible both manually and programmable. This enlarge the Complexity of the whole system, making it more prone to errors.
Producability	What is the amount of non-standardised items included in the design. What items cannot be bought in the stores. Items that need to be specially designed and fabricated are expensive and have a long fabrication time.
Built in speed	The setup needs to be installed into a continuous working washing line, thus it is important that the washing line can continue as fast as possible.
Costs	To produce the setup and maintain the setup, the production costs should be low.
Maintenance	The system needs to be built into an already existing washing line, which is in continuous use. It is important that the setup does not need much maintenance and is very robust to ensure no error would occur. Which can result in a complete stop of the washing line.
Size	The system needs to be placed inside the dirty room of the washing line, this means that relative limited space is available.

TABLE 15. EXPLANATION POINTS HARRIS PROFILE

	- - (min min)
Adaptability	There is no way to adapt the system (exclude frame and tank) without using heavy power tools and there is limited space aviable.
Controllable efficiency	There is absolutely no option to control or alter the flow when the system is installed.
Base efficiency	Heat transfer system without counter flow option.
Complexity	more then 2 sensors or more then 2 pumps are involved to operate the flow through the system
Producability	More then 5 Non-standarised items.
Built in speed	The operation of the washing disinfection machines need to be stalled for more then 1.5 hours.
Costst	Above 3000,-
Maintenance	2 or more moving part in the system and more then 50 connecting pieces that could leak and minimum of 8 electrical components.
Size	shell and tube heat exchanger outside the tank and more then 30 components used.
	-(min)
Adaptability	There is no way to adapt the system (exclude frame and tank) without using heavy power tools but there is enough space aviable.
Controllable efficiency	Control the flow with use of external tools e.g. screwdriver.
Base efficiency	Heat transfer system with counter flow option and a maximum thermal transfer of 20 %.
Complexity	2 sensors and two pumps are involved to operate the flow through the system
Producability	4 Non standarised items.
Built in speed	The operation of the washing disinfection machines need to be stalled between 1.5 and 1 hours.
Costst	Between 3000,- and 2000,-
Maintenance	1 moving parts and 40 connecting pieces and a maximum of 5 electrical components.
Size	plate heat exchanger outside the tank and more then 30 components used.
	+ (plus)
Adaptability	Alternation of water flow within the system can be made without use of any power tools or the design can easily be extended by use of ”copy” and ”paste” a sequel.
Controllable efficiency	Manual control and alter the flow without use of any tools that are not included in the design.
Base efficiency	Heat transfer system with counter flow option and use of shell and tube heat exchanger.
Complexity	2 sensor and one pump is involved to operate the flow through the system.
Producability	3 Non standarised items.
Built in speed	The operation of the washing disinfection machines need to be stalled between 1 hour and 30 minutes.
Costst	Between 2000,- and 1500,-
Maintenance	0 moving parts and 35 connecting pieces and a maximum of 3 electrical components.
Size	Maximum 20 components outside the tank and heat exchanger outside the tank.
	++ (plus plus)
Adaptability	Alternation of water flow within the system can made without use of any tools.
Controllable efficiency	Computer control and alter the flow without use of any tools that are not included in the design.
Base efficiency	Heat transfer system with counter flow option and use of plate heat exchanger.
Complexity	1 sensor and one pump is involved to operate the flow through the system.
Producability	2 Non standarised items.
Built in speed	The operation of the washing disinfection machines need to be stalled for less then 30 minutes
Costst	Below 1500,-
Maintenance	0 moving parts and 30 connecting pieces and a maximum of 2 electrical components.
Size	Heat exchanger within the tank.

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TABLE 16. HARRIS PROFILE

	Concept 1				**Concept 2**				**Concept 3**				**Weight**
	- -	**-**	**+**	**++**	**- -**	**-**	**+**	**++**	**- -**	**-**	**+**	**++**	
Adaptability			+				+	++			+	++	5
Controllabe Efficiency		-				-					+	++	5
Base efficiency	- -	-					+				+	++	4
Complexity			+	++			+	++		-			3
Producability			+				+	+			+	+	3
Built in speed			+	+		-				-			2
Costs			+				+	+	- -	-			2
Maintenance		-					+	+		-			2
Size			+	++	-	-				-			2
Total Score	**13**				**23**				**21**				

	Concept 1
Adaptability	The coil is located inside of the tank within the tank is not much space to adjust thing. The possibilities to add other heat exchange elements into the setup is very promising.
Controllable efficiency	The only part of the design to improve the efficiency is to alter the rotation speed of the rotor, this requires more energy.
Base efficiency	It is commonly accepted that the helical coil heat exchange does have a low heat transfer capacity.
Complexity	The design has straightforward working principles. By including a solenoid, and a rotor the design is increasing in complexity .
Producability	The coil should fit into the tank thus either one of the two might need to be specially made. The propeller located into the coil in the tank might need to be specially made as well.
Built in speed	The coil is installed in the tank already, thus not much piping need to be done for installation.
Costs	Some parts need to be made to fit, this is commonly more expensive then buying standard fit.
Maintenance	There is a large moving part (propeller) in the tank, moving parts are always susceptible to maintenance.
Size	The heat exchange mechanism is installed into the tank which saves spaces outside of the tank. Even though the tank might slightly be larger then the other concepts.

	Concept 2
Adaptability	There is a lot of room to add electronic equipment to improve the overall performance of the set up.
Controllable efficiency	There are a no pumps or other electrical systems included in the design, which makes the only parameter to alter the flow is the valve and it's height.
Base efficiency	Hot fluid will flow directly when emptied by the machines through the heat exchanger. A couple of seconds later the boiler will pump clean water through the HEX, in this period some hot fluid is lost in the sewage.
Complexity	There is no electrical system required for the setup of the system which makes the design rather simplistic in use.
Producability	There are no special components needed for this design.
Built in speed	There are limited pipes that need to be installed into the already existing sewage network. All the equipment need to be fixated and supported .
Costs	There are no electronic sensors or actuators involved in this design. Also there are no special components needed.
Maintenance	There are no moving parts or electronics in the design which makes it less susceptible to maintenance.
Size	It is larger then concept 1 and 3. But can still fit perfectly fine in the space aviable.

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	Concept 3
Adaptability	The concept is due to its electronics tweekable, but the possibilities to add electronic equipment are more limited due to the needs to work together with the already existing electronics.
Controllable efficiency	With an increase or decrease of the flow velocity the efficiency of the PHEX is easily regulated. There is a limited amount of hot water flowing though the system without exchanging its heat.
Base efficiency	A plate heat exchanger is commonly known as the most efficient heat transfer mechanism.
Complexity	There is a large amount of programming necessary in this design, to minimize the chance of destruction of the pumps and to optimize the energy transfer between the clean and dirty water flow.
Producability	There are no special components needed for this design.
Built in speed	The build in speed is lower then concept 1 but should be about the same as concept 2.
Costs	There are some electric components included in the design which makes the design more expensive.
Maintenance	There are some electronic parts that can be suspectible to errors, also the PHEX is known for its chance for leaking.
Size	PHEX is more compact then the STHEX but larger then concept 1.

Appendix I: System characterization

A comprehensive numerical analysis of the Shell and Tube Heat Exchanger is currently not possible. However, some rough numerical calculations are necessarily. This provides insight into the factors that influence the heat exchanger performance. While CFD (continuum fluid dynamics) simulations are planned, they are sub optimal due to their high RAM usage during computation. Therefor, a limited number of simulations are conducted to gain an initial starting point for experimental calibration. The results of the simulations are depicted in Appendix J . The optimal mass flow velocity and pump characterised are listed as well.

Set up for characterization

The main point of interest in this chapter is the flow velocity of the hot water and cold water and their impact on the total heat transfer. The design will incorporate the ability to recirculate the dirty water, resulting in a flow velocity that can be altered by creating an "unlimited" amount of water. Consequently, a change in flow velocity will impact the Reynolds number in the shell side of the heat exchanger to maximize the performance. To get knowledge into the performance of the heat exchanger some calculations are necessary, with help of Matlab, a dedicated code is written see Appendix M. This code provide knowledge in the different dimensionless properties of the flow in combination with the free to be designed parameter of the water flow speed of the dirty and clean fluid. An increase in the Nusselt number, equate to a higher heat transfer coefficient. Notably, the Nusselt number increase with an increasing mass flow velocity. In the literature review done prior to this research, see Appendix M, it was noticed that a higher Reynolds number will increase the amount of fouling occurring in the heat exchanger. Fouling will occur in the viscous sub layer of a turbulent flow, the higher the turbulence of the flow, the thicker the viscous sub layer is, see figure 26. It is noticed that fouling can occur in the heat exchanger and impact the system negatively. A high mass flow velocity, will require more pumping power then energy being transferred. Therefore an optimum is needed to be found. In present day times the equations for the fouling processing still need to be developed. This Appendix explains the importance of a high flow velocity but also the pressure drop in the HEX will be addressed.

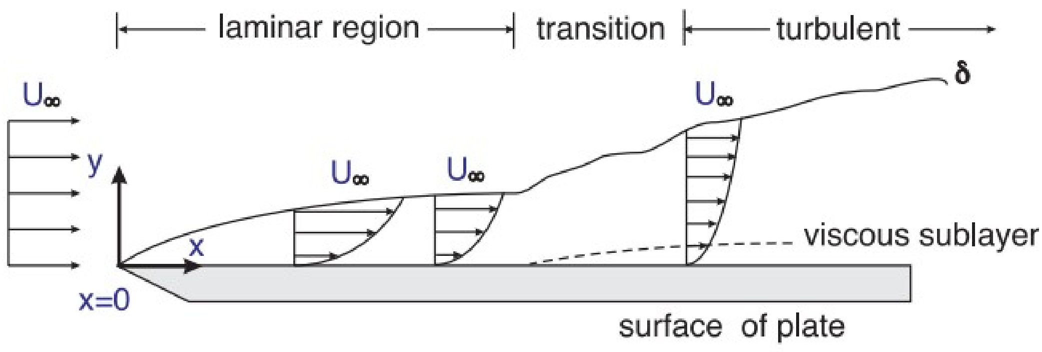

Fig. 26. Visualisation of the increase in velocity of the flow resulting in an increase of the Reynolds number and a thicker viscous sublayer.

To provide insight into the influence of different flow speeds, calculation with Matlab are made. The Reynolds number and heat transfer coefficient are compared with an increasing flow velocity. Furthermore, The pumping power needed for a specific mass flow rate is stated. Also the need of energy to heat the cold clean water till a certain temperature is depicted. The initial cold clean water temperature is assumed to be 15 °Celsius. The simulations in Solidworks are done at a temperature of 60 °Celsius because 60 % of the effluent is that temperature. This should provide information to limit the amount of computational simulations needed. Consequently extended simulations with Solidworks are conducted in order to gain an optimal setup to use in the final design.

Numerical calculation

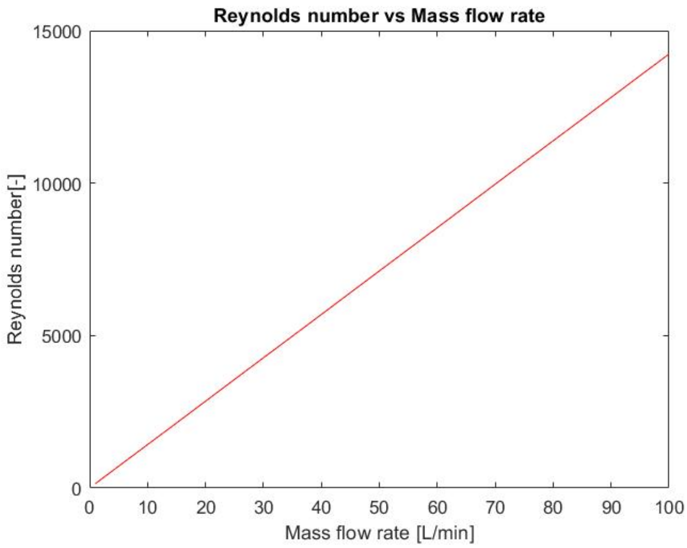

Fig. 27. Reynolds number plotted against the mass flow rate in the tubes.

In figure 27 the y-axis represent the Reynolds number, while the x-axis represent the mass flow rate. The flow starts in the laminar region, this laminar region is till 2300 Reynolds number. The characteristic behaviour of the laminar flow can be seen until a mass flow rate of 16 liters per minute. The transition region of the flow range from a value of 2300 Reynolds number till 4000 Reynolds number. After the Reynolds number of 4000 is passed, the flow is noted as completely turbulent. Notably, the flow is turbulent at a flow rate of 24 liters per minute. Concluding from this graph is to start the simulations at 20 liters per minute.

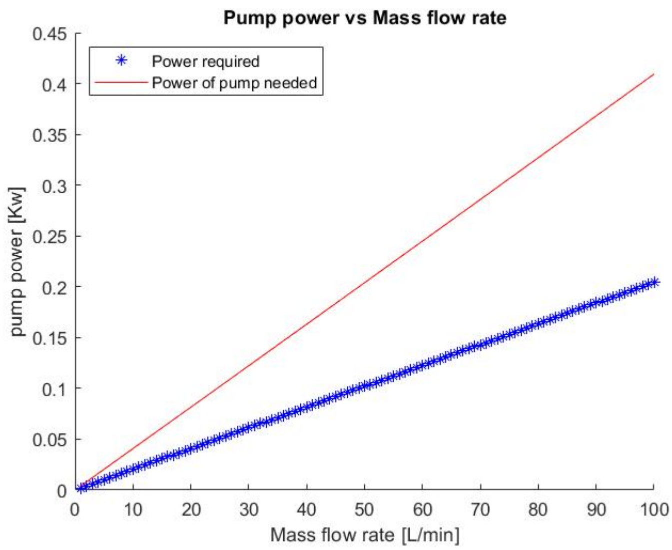

Fig. 28. Pump power that is needed for a specific flow rate. Red line (-) is the pumping power needed including the efficiency factor.

Figure 28 illustrates the relationship between increasing pumping power (y-axis) and the increasing in mass flow rate (x-axis). The figure reveals that with an increase in mass flow rate, an increases in pumping power is needed. It is worth noting that the estimated factors regarding water height and amounts of bends in the system have an impact on these results. The blue line indicates the power needed to overcome the forces to move the water with a certain speed. The actual pumping power required could be a bit higher, the red line indicated the pumping power with a common 50% efficiency of a typical pump. The graph suggests that for a 10 liters per minute hot flow increase, an additional 0.05 kW is needed to operate the pump.

In figure 29, illustrates the relationship between the heat transfer coefficient (y-axis) and the mass flow rate of the hot effluent through the HEX (x-axis). The graph illustrates that for an increase in velocity of the water flow through

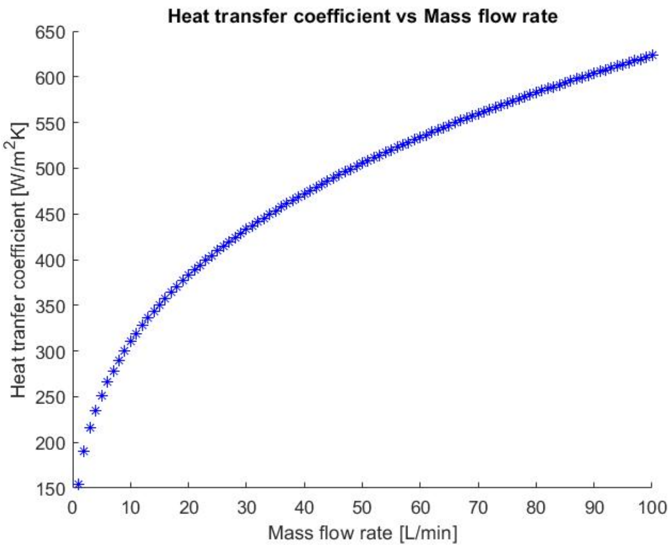

Fig. 29. The heat transfer coefficient is plotted against themass flow rate in the tubes.

the HEX there is an increase in heat transfer coefficient. However, this increase in velocity also leads to a greater pressure drop due to the elevated flow speed. Notably, it can be seen that during the laminar region of the flow, the heat transfer coefficient seems to experience reversed exponential growth. If the flow transition in a completely turbulent state, the heat transfer coefficient seems to be more linearly increasing.

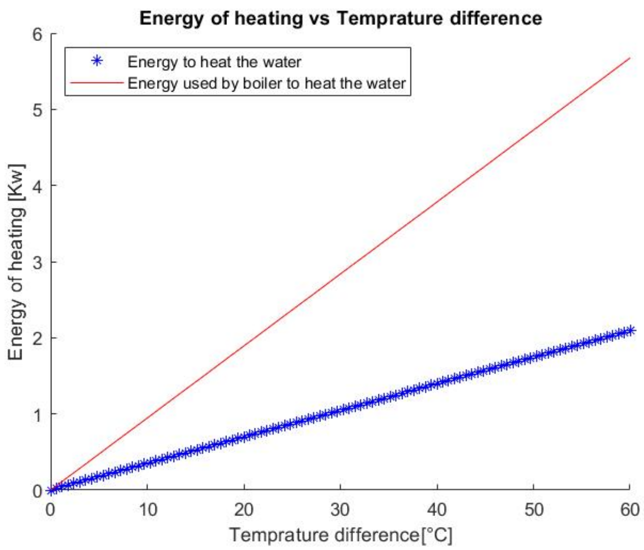

Fig. 30. The blue line (*) shows the energy that is needed to heat up 35 liters of water per degree Celsius. The red line(-) indicates the energy consumed by the external boiler with 36.8% efficiency.

Figure 30 illustrates cold water heated to the maximum temperature of 60 degree Celsius (depicted on the graph as 45 °Celsius difference), approximately 1.5 kW of energy is transferred from the hot water to the cold water. The external boiler (characterised by the red line) has an efficiency of 36.9%, implying the heated clean water saves almost three times the amount of energy salvaged from the hot dirty water. Notably, it can be seen that a 10 °Celsius increase of the cold water results in a energy save of 0.8 kW.

Figure 28 presents the pumping power needed (characterised by the blue line) and the actual pumping power with 50% efficiency(characterised by the red line). It can be seen that the pumping power increases linearly. An increase of 10 liters per minute pumping dictates a 0.05 kW power increase.

In reference to figure 30 it becomes evident that if the cold water temperature is raised with an additional 1 °Celsius, in the external boiler, 0.08 kW is needed. Through a combination of the information into an equation that describes the energy need for the water temperature to raise. The equation compares the energy required to heat the water in the external boiler against the energy needed to pump the water in a certain mass flow. 0.05/0.08 = 0.625 °Celsius per 10 liter per minute. An increase of 0.625 °Celsius of the cold water is needed to equate the energy required for the pump to move an additional 10 liters per minute. This point of equilibrium is guessed at a maximum of 100 liters per minute.

Concluding to do simulations between 20 liters per minute and 70 liters per minute, or until the pump requires more energy then the heat exchanger transfer heat.

Appendix J : Results simulations

A single simulation of the Computation Fluid Dynamics (CFD) runs for 8 hours, a series of simulations have been conducted to get expectations and knowledge about what different alternations in the fluid flow velocity results in and what the characterises for the pump should be. Table 19 and table 18 provides an overview of the outcome of the simulated values. The findings of these tests are expected to help narrow down the the optimal setup for the HEX system. Initially, the simulation involves the cold water flow (15 °Celsius) at a rate of 16 liters per minute, which correspond to the mass flow rate at Greencycl. The hot water (60 °Celsius) flow will be simulated with a flow of 20, 30, 35, 40, 45, 50 and 70 liters per minute. These simulations are also conducted at a restricted cold water flow rate of 12 liters per minute for a overview see Table .

TABLE 17. Values used for the simulations to find the most optimal flow velocity for the desired heat exchanger.

Cold water flow (L/min)	Hot water flow (L/min)
	10
	20
12	30
16	35
	40
	45
	50
	60
	70

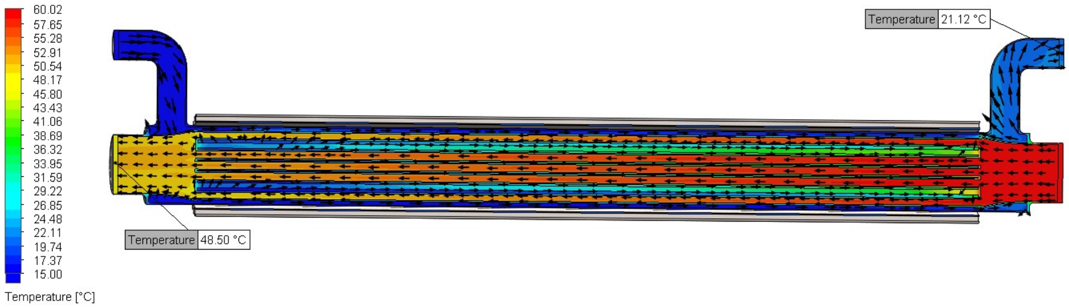

Fig. 31. CFD simulation on Solidworks with a 10 L/min hot water flow and 16 l/min cold water flow.

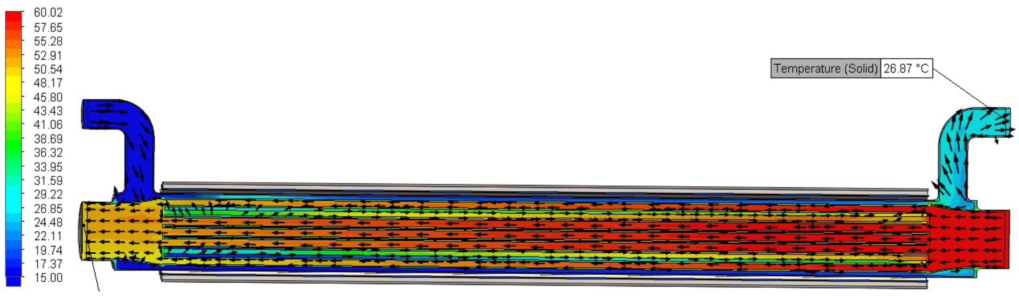

Fig. 32. CFD simulation on Solidworks with a 20 l/min hot water flow and 16 L/min cold water flow.

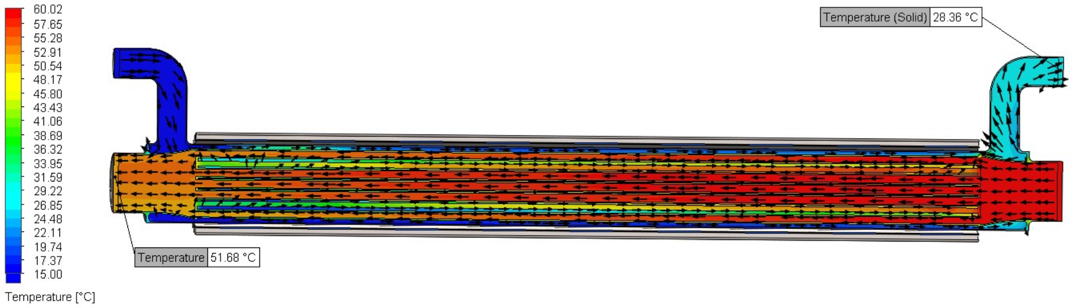

Fig. 33. CFD simulation on Solidworks with a 30 l/min hot water flow and 16 l/min cold water flow.

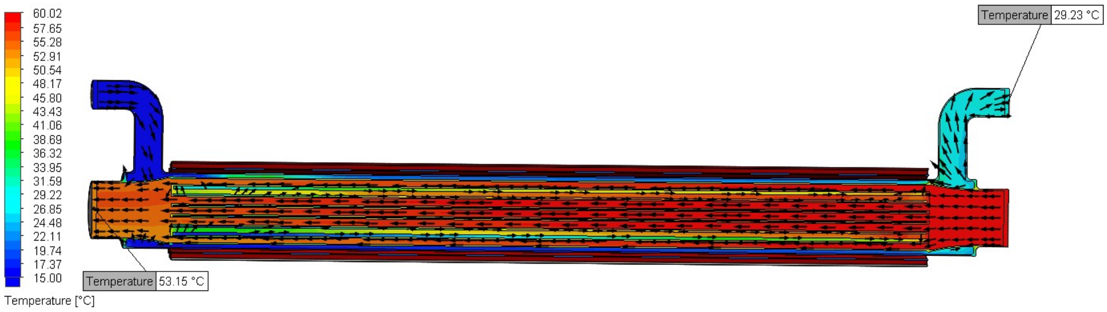

Fig. 34. CFD simulation on Solidworks with a 40 l/min hot water flow and 16 l/min cold water flow.

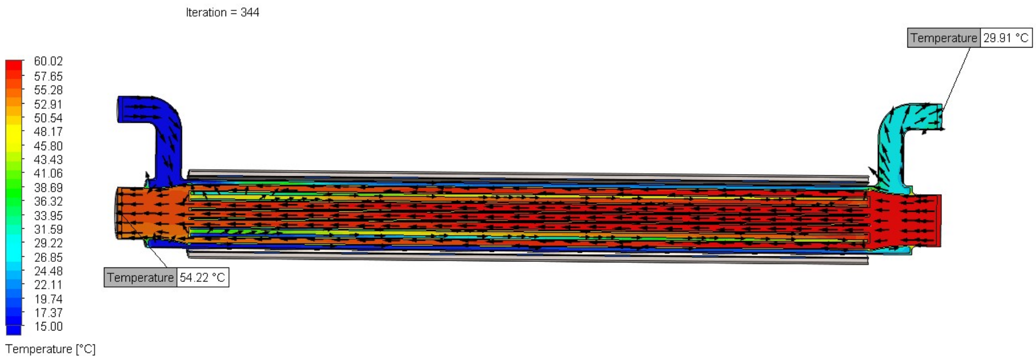

Fig. 35. CFD simulation on Solidworks with a 30 l/min hot water flow and 16 l/min cold water flow.

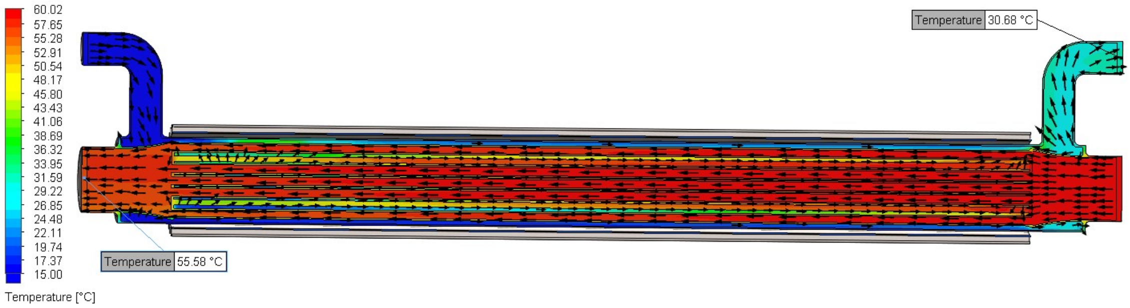

Fig. 36. CFD simulation on Solidworks with a 70 l/min hot water flow and 16 l/min cold water flow.

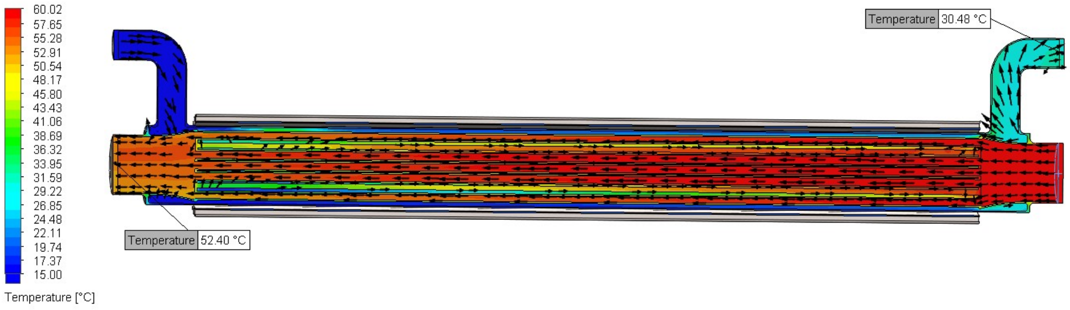

Fig. 37. CFD simulation on Solidworks with a 30 l/min hot water flow and 12 l/min cold water flow.

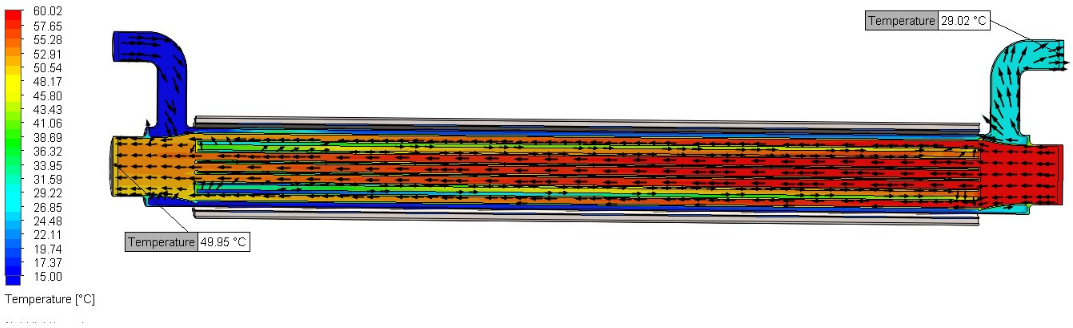

Fig. 38. CFD simulation on Solidworks with a 20 l/min hot water flow and 12 l/min cold water flow.

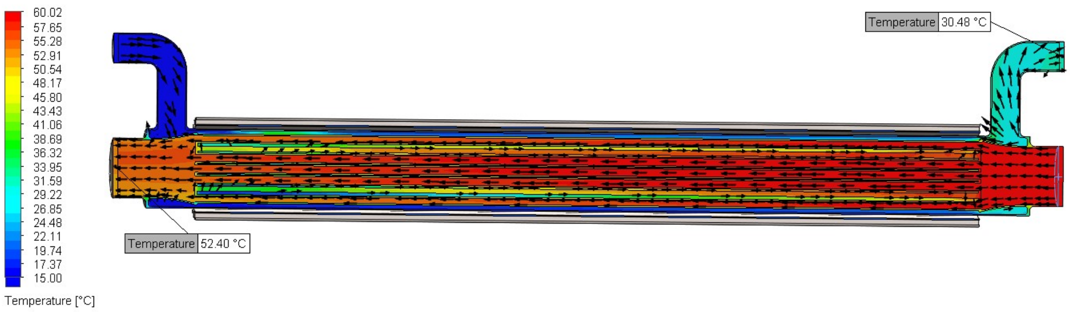

Fig. 39. CFD simulation on Solidworks with a 30 l/min hot water flow and 12 l/min cold water flow.

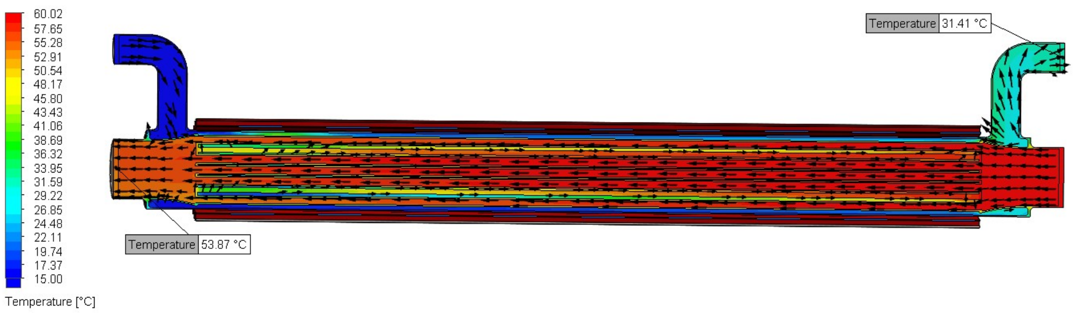

Fig. 40. CFD simulation on Solidworks with a 40 l/min hot water flow and 12 l/min cold water flow.

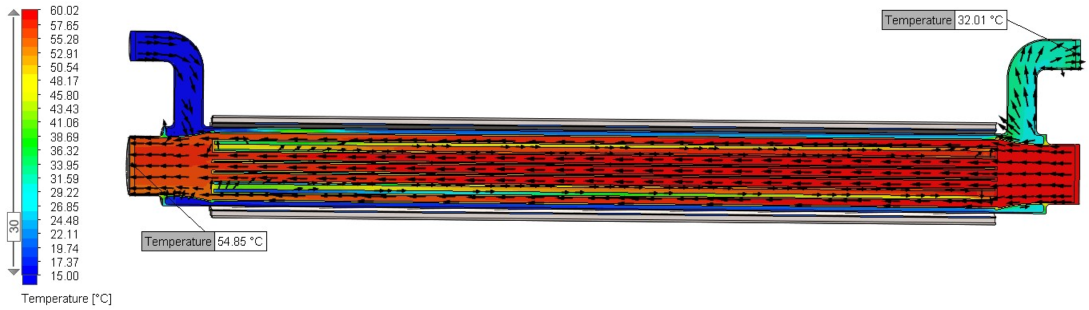

Fig. 41. CFD simulation on Solidworks with a 50 l/min hot water flow and 12 l/min cold water flow.

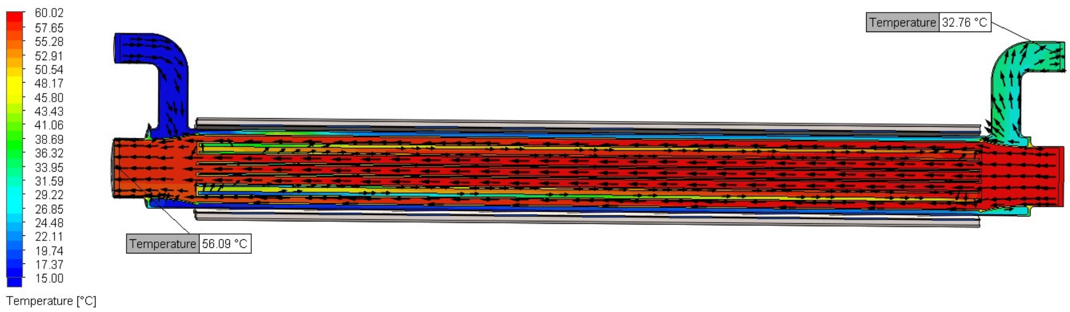

Fig. 42. CFD simulation on Solidworks with a 70 l/min hot water flow and 12 l/min cold water flow.

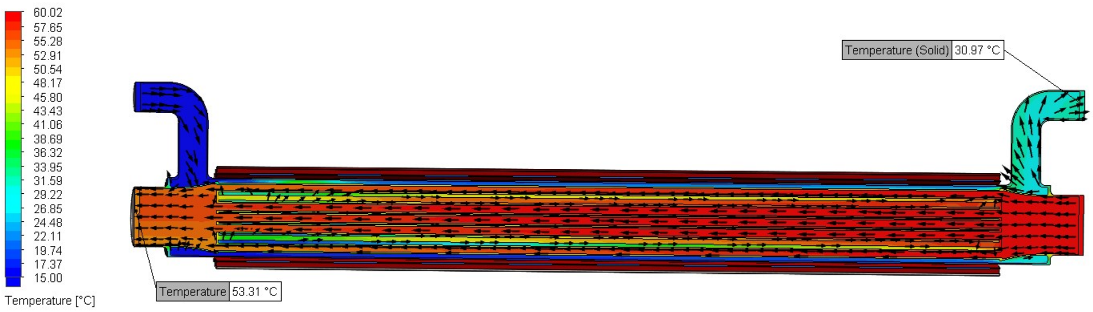

Fig. 43. CFD simulation on Solidworks with a 35 l/min hot water flow and 12 l/min cold water flow.

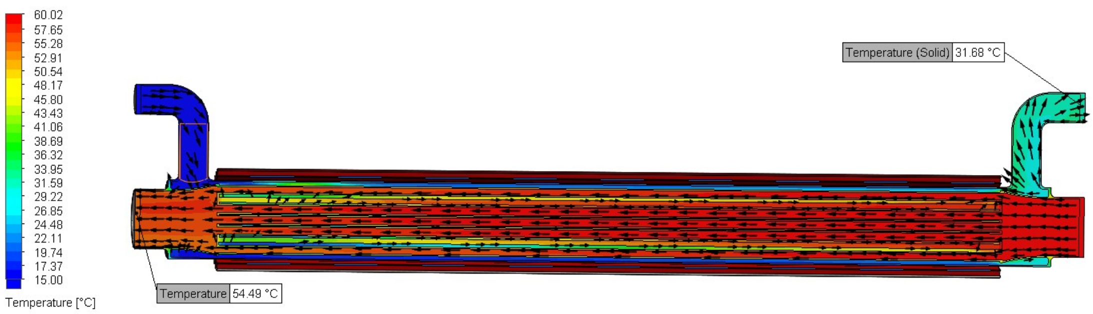

Fig. 44. CFD simulation on Solidworks with a 45 l/min hot water flow and 12 l/min cold water flow.

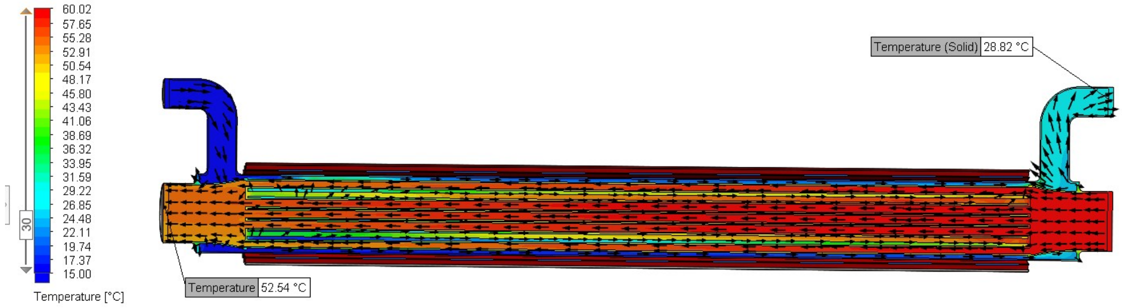

Fig. 45. CFD simulation on Solidworks with a 35 l/min hot water flow and 16 l/min cold water flow.

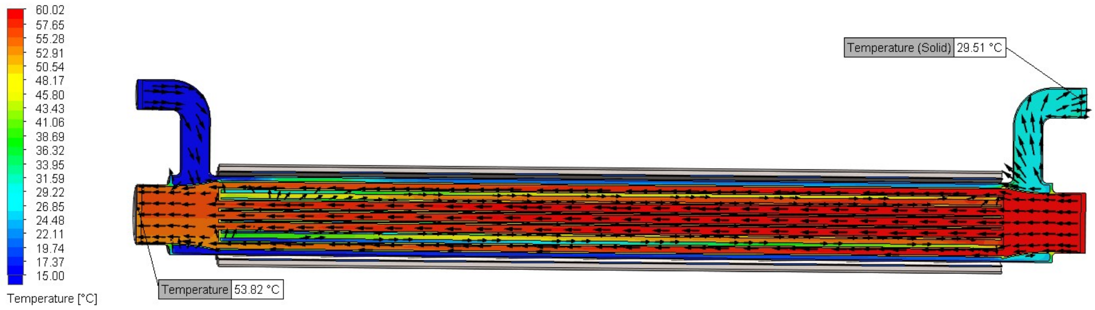

Fig. 46. CFD simulation on Solidworks with a 45 l/min hot water flow and 16 l/min cold water flow.

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TABLE 18. HEX OUTLET WATER TEMPERATURE IN °CELSIUS OF THE CLEAN SIDE.

		Cold water flow [L/min]	
		12	16
Hot Water Flow [L/min]	10	-	21.21
	20	29.02	26.87
	30	30.48	28.36
	35	30.97	28.82
	40	31.41	29.23
	45	31.69	29.51
	50	32.01	29.91
	60	-	-
	70	32.68	30.68

TABLE 19. HEX OUTLET WATER TEMPERATURE IN °CELSIUS OF THE DIRTY SIDE.

		Cold water flow [L/min]	
		12	16
Hot Water Flow [L/min]	10	-	48.50
	20	49.95	49.65
	30	52.40	51.68
	35	53.31	52.54
	40	53.87	53.15
	45	54.49	53.82
	50	54.85	54.22
	60	-	-
	70	56.09	55.58

.

APPENDIX K: MATLAB CODES

```
%non-specific parameters
rho =985.7 %[kg/m^3]
mu= 0.0005036   %[Ns/m^2]
nu= 5.109*10^-7  %[m^2/s]
alpa=0.000018 %[m^2/s]
k= .144 %[W/(m*k)]
g= 9.81 %[m/s^2]
er= 1.0*10^-7 %m %surface roughness of titanium
m= 30 %L of cold water
c= 4.187 % Kj/Kg*k
T= linspace(0,60,100)

%AREA OF FLUIDS IN THE HEX
AB=0.003216 %m^2   %total surface area of HEX
DB=0.006      %m  %radius of tube inner hot fluid diameter
%37 pipes
L= 1 %m %FLOW LENGHT IN THE HEX
Cs= 0.0196 %m circumference per hole
As= Cs*37*L %surface area of tubes
Ap=0.001841  %1841 mm^2 %surface area of cold fluid in HEX
Ac= AB-Ap % m^2 % surface area of hot fluid in HEX

Ql=linspace(1,100,100) %[L/min] %flow of hot water through
the hex
Q= 1.*Ql/(1000*60) %[m^3/sec] van Ql L/min
v=  1.*Q./Ac %[m/s]

%TEMPRATURE
Tin= 15 %[graden C]

%EQUATIONS
Dh= (4*Ac*L/As)% HYDRODYNAMIC DIAMETER
W=(er/(3.7.*Dh)).^1.11 %part of the fD formula.
Re = (rho.*v.*DB)/mu %REYNOLDS NUMBER
Pr= 3 %BETWEEN 1-13 FOR WATER
f= 0.25./(log((er/3.7.*Ac)+(5.74./Re.^0.9)).^2) %tussen 0.01
en 0.1%colebrook equation
fD=(-1.8.*(log((6.9./Re)+W))).^-2 %DARSY FRICTION
FACTOR,ACCORDING TO THE HAALAND CORROLEATION

nabla = 1.*k/(0.5.*Dh)
I= (f/8).^0.5 %part of the Gnielinski formula
Nus= 1.045.*Re.^(0.303)*Pr.^(0.287)
```

```
Nug= (fD/8).*(Re-1000).*Pr/(1+12.7.*I.*(Pr.^(2/3)-1))
%nusselt number thorugh the corroleation of Gnielisnki
hs=(Nus*k)/DB
hg=(Nug*k)/DB


% POMPLOSSES IN TOTAL


Pd= rho*fD*L.*v.^2./(2.*Dh)/100000 % {bar]DARCY WEISBERGH
%frictionlos
Po =0.1 %[bar] height
Pv=Ql.*(1+Pd+Po)/540 %[KW]
PVT= Pv.*2

%Temprature calculations
Pw=m*c*T/3600

Pww=Pw/0.369

%MAKING OF FIGURES.

figure
hold on
plot(Ql,Pd)
%plot(v,Nug)
title('Pressure Drop vs Mass flow rate')
ylabel('Pressure drop [bar]')
xlabel('Mass flow rate [L/min]')
hold off

figure

hold on
plot(Ql,Pv,'*','color','blue','DisplayName','Power
required')
plot(Ql,PVT,'-','color','red','DisplayName','Power of pump
needed')
title('Pump power vs Mass flow rate')
ylabel('pump power [Kw]')
xlabel('Mass flow rate [L/min]')
legend('Power required','Power of pump
needed','Location','northwest')

hold off
```

```
figure
hold on
plot(T,Pw,'*','color','blue','DisplayName','Energy to heat
the water')
plot(T,Pww,'-','color','red','DisplayName','Energy used by
boiler to heat the water')
title('Energy of heating vs Temprature difference')
ylabel('Energy of heating [Kw]')
xlabel('Temprature difference[C]')
legend('Energy to heat the water','Energy used by boiler to
heat the water','Location','northwest')

hold off

figure
hold on
plot(Ql,hs,'*','color','blue')
plot(Ql,hg,'-','color','red')
title('Heat transfer coefficient vs Mass flow rate')
xlabel('Velocity [m/s]')
ylabel('Heat tranfer coefficient [W/m^2K]')
hold off



figure
hold on
plot(Ql,f,'-','color','blue')
plot(Ql,fD,'*','color','red')
title('Friction factor vs Mass flow rate')
xlabel('Mass flow rate [L/min]')
ylabel('Friction factor')

hold off
figure
plot(Ql,Re,'-','color','red')
title('Reynolds number vs Mass flow rate')
xlabel('Mass flow rate [L/min]')
ylabel('Reynolds number[-]')
```

APPENDIX L: ARDUINO CODES

```
// Pins PROGRAM FOR EXPERIMENT
const int LIQUID_SENSOR_PIN = 8; //red in 3.3V
const int RELAY = 6;
const int LED = 4;
const int BUTTON = 10;

void setup() {
  pinMode(LIQUID_SENSOR_PIN, INPUT);
  pinMode(BUTTON,INPUT);

  pinMode(RELAY, OUTPUT);
  pinMode(LED, OUTPUT);

  digitalWrite(RELAY, LOW);
  digitalWrite(LED,LOW);
  Serial.begin(9600);
}
```

```
void loop()
{
  if( digitalRead(LIQUID_SENSOR_PIN)==0 && digitalRead(BUTTON)==0){
 Serial.println( "water is detected and pumps  ");
    digitalWrite(LED,HIGH);
    digitalWrite(RELAY, HIGH);
      while (digitalRead(LIQUID_SENSOR_PIN)==0){
       digitalWrite(LED,LOW);
        }

  }
  else if ( digitalRead(LIQUID_SENSOR_PIN)==0 && digitalRead(BUTTON)==1 ) {
    digitalWrite(RELAY, LOW);
    digitalWrite(LED,HIGH);
    Serial.print( "water is detected");
  }

  else {
    Serial.println( "tank is empty");
    digitalWrite(LED,LOW);
    digitalWrite(RELAY,LOW);
}


  int but = digitalRead(BUTTON);
  int sensor= digitalRead(LIQUID_SENSOR_PIN) ;
  Serial.println(sensor ); //TEST WORKING OF THE SENSOR
 Serial.println(but );  //TEST WORKING OF THE BUTTONS
  delay(2000);
}
```

Fig. 47. Arduino code used for the experiment.

.

```
// Pins PROGRAM FOR EXPERIMENT
const int LIQUID_SENSOR_PIN = 8; //yellow in 3.3V, blue in GND
const int RELAY = 6;


void setup() {
  pinMode(LIQUID_SENSOR_PIN, INPUT);


  pinMode(RELAY, OUTPUT);


  digitalWrite(RELAY, LOW);
  Serial.begin(9600);
}

void loop()
{

 if ( digitalRead(LIQUID_SENSOR_PIN)==0  ) {
    digitalWrite(RELAY, HIGH);

    Serial.print( "water is pumped");
  }

  else {
    Serial.println( "tank is empty");
    digitalWrite(RELAY,LOW);
}



  delay(2000);
}
```

Fig. 48. Arduino code used for the normal operation of the heat exchange system.

.

```
#include <LiquidCrystal.h>
#include "thingProperties.h"
#include "max6675.h"
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);
int thermoDO = 12;
int thermoCS1 = 13;
int thermoCS2 = 15;
int thermoCS3 = 0;
int thermoCS4 = 2;
int thermoCLK = 14;
int flow1 = 10;
int flow2 = 9;
MAX6675 thermocouple1(thermoCLK, thermoCS1, thermoDO);
MAX6675 thermocouple2(thermoCLK, thermoCS2, thermoDO);
MAX6675 thermocouple3(thermoCLK, thermoCS3, thermoDO);
MAX6675 thermocouple4(thermoCLK, thermoCS4, thermoDO);
float tco = 0;
float tho = 0;
float tci = 0;
float thi = 0;
const int buttonPin1 = 16;

int buttonState = 0;
void setup() {
  pinMode(buttonPin1, INPUT);

  Serial.begin(9600);

  initProperties();

  ArduinoCloud.begin(ArduinoIoTPreferredConnection);

 setDebugMessageLevel(2);
 ArduinoCloud.printDebugInfo();

 lcd.init();
 lcd.backlight();      // Make sure backlight is on
 lcd.setCursor(0, 0);  //Set cursor to character 2 on line 0
 lcd.print("GREEN  DASHBOARD");
 lcd.setCursor(4, 1);  //Move cursor to character 2 on line 1
 lcd.print("By Team 1");
 // wait for MAX chip to stabilize
 delay(3500);

}

void loop() {

 ArduinoCloud.update();
 // Your code here
 onTempcoldoutChange();
 // onFlowrateColdChange();
 // onFlowrateHotChange();

 Serial.print("temp1 C = ");
 Serial.println(thermocouple1.readCelsius());
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print("T1=");
 lcd.print(thermocouple1.readCelsius());
 delay(10);
 Serial.print("temp2 C = ");
 Serial.println(thermocouple2.readCelsius());
 lcd.setCursor(8, 0);
 lcd.print("T2=");
 lcd.print(thermocouple2.readCelsius());
```

Fig. 49. K-thermocouple sensor Arduino code. [1/2]

```
  lcd.setCursor(8, 0);
  lcd.print("T2=");
  lcd.print(thermocouple2.readCelsius());
  delay(10);
  Serial.print("temp3 C = ");
  Serial.println(thermocouple3.readCelsius());
  lcd.setCursor(0, 1);
  lcd.print("T3=");
  lcd.print(thermocouple3.readCelsius());
  delay(10);
  lcd.setCursor(8, 1);
  Serial.print("temp4 C = ");
  Serial.println(thermocouple4.readCelsius());
  lcd.print("T4=");
  lcd.print(thermocouple4.readCelsius());
  delay(3000);
  lcd.noBacklight();
  buttonState = digitalRead(buttonPin1);

  if (buttonState == HIGH) {
    lcd.backlight();
    delay(3000);
    buttonState == LOW;
  }
  else
  {
    lcd.noBacklight();
  }
}

void onTempcoldoutChange()  {


  void onTempcoldoutChange()  {

    tempcoldout = thermocouple1.readCelsius();
    tempcoldin =  thermocouple2.readCelsius();
    temphotout = thermocouple3.readCelsius();
    temphotin = thermocouple4.readCelsius();

  }

  void onTempcoldinChange()  {

  }
```

Fig. 50. K-thermocouple sensor Arduino code. [2/2]

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Appendix M: literature review

A literature study on the environmental footprint of the CSSD and the potential reduction with using a heat exchanger.

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Literature review period: 06-03-2023 until 28-04-2023

***Abstract*—The environmental footprint of the CSSD is investigated in his paper. Research highlighted the contribution of carbon emissions during the cleaning, disinfection and sterilization in the total life time of reusable instruments. The water and power usage of the washer disinfection machine and the sterilizer is investigated to gain knowledge of the environmental footprint. With this knowledge a heat exchanger to decrease the energy usage is suggested. An overall heat exchanger and the two most used: a tube-and-shell heat exchangers and plate heat exchangers are investigated. Information is presented about fouling, calculating and modeling of the two different heat exchangers**

I. Introduction

The Netherlands [1], UK [2] and the US [3] hospitals contribute to between 4% and 10% of the total Carbon emissions in their region. The two major departments in the hospitals contributing to this carbon emission is the operation theatre and the CSSD [4] their contribution summed between 10% and 24% of the total. In Paris in the year 2019 according to Lemonnier et all about 73% of CO2 production of the Central sterilization supply demand unit is caused by the usage (heating e.g.) of water [5]. The amount of CO2 emission can be correlated to the energy consumption and thus the costs [6]. The Dutch government set a deadline in 2050 to realise a climate neutral healthcare. In the year 2030 a reduction of 49% of the carbon emission compared to the 1990 levels should be achieved [7]. To decrease the amount of water-waste with valuable energy and thus reach a reduction in the CO2 emission, energy costs. Adjustments need to be made in the waste-water drainage. A possibility to build-in a water heat exchanger in an operating washer-disinfection machine and steam sterilizers is proposed. In the disinfection phase about 30 liters of water between 90 and 93 degree Celsius is used this normally would be drained away [8]. It is proposed to use the heat exchanger to preheat the incoming water for the washing phase, about 40 Liters of water up to about 43 degree Celsius.

Research Goal:

1) Gain insight in the amount of CO2 production, water consumption and energy consumption.
2) Evaluate the necessity of a heat exchanger.
3) Gain insight in designs and working mechanisms of heat exchangers and which designs are most promising for this application.

II. Method and Scope

The first step before setting up a research question is to determine the objectives of what information should be the outcome of the literature research.

The objective are set up with help of the **SMART** way. This meant that objectives should be: Specific, Measurable, Achievable, Relevant and Time-based. This will help with setting up objectives that can have a measurable specific objective this can be done by a clearly written goal to keep the research narrow and focused on quantitative information. It is also desired to have the objectives in a relevant, achievable and time-based fashion to make the scope of the research in limit of the budget, time period and interest, this can help to stay motivated.

Objectives:

- Gain knowledge about the amount of energy used in a CSSD facility.
- Gain knowledge about the overall footprint of a CSSD facility.
- Gain knowledge about the working of different water heat exchangers.
- Gain knowledge about how to choose/design the right water heat exchanger.

.

The knowledge of the objectives for this search led to the initial research question:
What is the amount of *energy* used by a *washer-disinfection* cycle in a hospital *cleaning and desinfection facility*, and how to facilitate the *reuse of the valuable waste energy* to *preheat water* for the cycle?

A. Separation Of Research Question

To answer the research question, two sub-questions are added. The first sub question will focus mainly on the Energy, CO2 emission and water consumption of the central sterile supply department(CSSD) to gain knowledge about the scale of the so called problem. The second part of the sub question will focus more on the applications to exchange the heat left in the hot medium to the cold. This sub question should also provide knowledge of possibilities and designs for a high efficiency heat exchanger.

Sub-questions1:
What is the *environmental footprint* (CO2, Energy, water) used by the *disinfection machine* during the *cleaning* cycle in the CSSD *facility?*
sub-questions2:
What methods are available to re-use heat lost by means of *reusing the heat* in *water*?

B. Search Plan

With help of the Library of the TU Delft a setup for a search plan is made [9]. The first step in setting up a search plan to determine certain concepts that describes certain aspects of the subject.
The textual column of table II-B is what part of the question is noticed to be important. The concept column (third column) can be used for gathering of terms to use for the search query in the databases. This will be the starting point of the literate search. There are possibilities to add, subtract or alter the concepts. Specific terms for the general concepts can be seen in chapter III and IV.

SUBQ #	Textual	Concepts
1	Enviromental footprint	Enviromental footprint
1	Washer- desinfector machine	Department
1	Cleaning facility	Location
2	Reusing the heat	Heat exchange mechanism
2	Water	Medium

TABLE I. Initial conceptualization of terms used for the search of relevant articles.

C. Databases

A formulation of the search queries can be made and finally it need to be determined where this information is sought. In the initial state Scopus and GS is used to search. Scopus is used for the initial phase because Scopus has an extended options for logical operators, therefor it is easy to exclude all articles about for example medicine. On the other hand google scholar has less logical operators which resulted in usually more articles which are not all relevant. This resulted in some quite relevant articles in between a lot of non-useful articles about for example nanofluids. Espacenet will also be lightly searched in order to find specific information of machines and their gas consummation for example.

III. Literature search 1: footprint of CSSD

As discussed in chapter II the initial sub question to focus on in this part is stated as follow: **What is the environmental footprint (CO2, Energy, water) used by the water-disinfection machine cleaning cycle facility?**

The sub question was adapted during the initial search to: **What is the environmental footprint(CO2, Energy, water) consumed by the Central sterilization supply department?** It became quite clear that the scope of most researched found did not specify the washer-disinfection on itself, but researched the whole CSSD as one complete step in a process.

The initial steps to set up a proper search query can be read in subsection III-A. When the articles are found the inclusion criteria can be seen in subsection III-B. The inclusion criteria should be set up, to determine in a constant manner which titles and abstracts should be included or excluded to result in articles that have promising information to answer the sub question. The final search with added keywords and altered subjects can be found in subsection III-C

A. Exploring Search

The first steps taken in the exploring state is to search for some general information and knowledge on the internet. This gave a bit of information on some important aspects of a Central sterile supply department (CSSD). The Final subquestion used for research and concepts generation is : **What is the environmental fotoprint(CO2, Energy, water) consumed by the overal Central sterile supply department?**
As already stated in subsection II-B a proper sub question can be helpful to derived concepts for the search querry. The initial concepts with the subjects can be found in figure 1. To gain the subjects, synonyms for concepts need to be sought, this is done with help of *www.thesaurus.com* [10] the great advantage of this site is that the site not only finds the exact synonyms but also gives words that do not mean exactly the same and the site color code these words on the amount similarity of meaning. These synonyms will be combined with the word **OR** and the different concepts will be combined with the word **AND**. The "" in "medical clinic" are used to search on the word *medical clinic* and not on *medical* **AND** *clinic*. In Scopus it is an option to only search in the title, abstract and the keywords this function (**TITLE-ABS-KEY**) is used in all searched to decrease the amount of results. This is done because Scopus will find the words throughout the whole text even if the subject is listed just once.

Information is also sought on patent site: Espacenet [11], it is wished that through some patents, information about the water consumption, electricity and gas usage of washer disinfection machines and autoclave machines can be found. Another goal of the search in the patent base is to find general information and inspirational solution for the recovery of the heat. The search quarry that is used is as follow:
(**ctxt all** "washer desinfection" **OR ctxt all** "autoclave") **AND** (**ctxt any** "water" **OR ctxt any** "power" **OR ctxt any** "gas") **AND ctxt all** "heat exchanger" **AND (ctxt any** "reclaim" **OR ctxt any** "reuse" **OR ctxt any** "utilize")
ctxt stands for title, abstract or claim and mean that the words are searched in these places in the documents. This search query gave **287** results, The titles are scanned and some abstracts were read to gain knowledge about the working principles of the washing disinfection machines and steam sterilization mechanism.

The search queries which are shown are simplified. It would be a heap of words if all the subjects are listed therefor it is chosen to only list the concepts in this part to keep it organised. This meant that the search query in Scopus is consisting of the subjects instead of the concepts. To answer sub question one, the next queries of concepts are searched. For a overview, see figure 1. The first query that is searched is: **TITLE-ABS-KEY***(environmental footprint)* **AND** *(location)* this search query gave **33.000** result.When: **AND** *(department)* is added, **80** results where given. When the titles and abstracts were read about **33** can be promising for good information and for snowballing effect, see figure 5.

	Combine concepts with AND		
	Environmental footprint	**Department**	**Location**
Combine the search terms with OR	*Carbon emission Environmental impact Operational emission Greenhouse gas Medical waste Environmental Life cycle Footprint Energy consumption Impact*	*Central sterilization service -department Central sterilization Central sterilization service Central sterilization department Central sterile supply department Central sterile department Central sterile supply Sterile supply department Sterilization unit Washing and disinfection Decontamina Cleaning facility Cleaning unit Steam sterilization*	*Hospital Medical clinic Clinic Healthcare Health care*

Fig. 1. First version of concepts used in Scopus for finding relevant articles to answer sub question 1.

Unfortunately the search query was a bit narrow, but with great outcome. To not miss important information an additional search with an additional concepts is done as well an more broader subjects of the concepts of *department* is made. To determine the broader concepts a comparison between the keywords of the scanned articles already found are made to determine which subjects can be added to the search query. A specific keyword that is noticed a lot of times is the addition of water, effluent, sewage and water flow. Also Sustainability is added to the environmental footprint concept as well as green and ecological. Due to the change in sub question the term autoclave is added to the department subject, for the complete alterations of the search subjects see figure 2.

B. Inclusion And Exclusion Criteria

To gain useful articles a criteria should be setup to avoid missing relevant articles from the reference list while reading article titles. For sub question 1, the words for the *inclusion criteria* that are mentioned in the title must contain one of the following:

- Environmental or synonym
- Water
- Energy

For the abstract reading of sub question 1 the *inclusion criteria* for including the abstract for scanning potential, the abstract should consist of two of the three criteria:

- Environmental or synonym
- Water
- Energy

For sub question 1 the *exclusion criteria* are that should not be mentioned in the abstract are:

- Effectiveness or synonyms
- ”Some biological effect”

	Combine concepts with AND			
	Environmental footprint	**Department**	**Location**	**Medium**
Combine the search terms with OR	*Carbon emission Environmental impact Operational emission Greenhouse gas Medical waste Environmental Life cycle Footprint Energy consumption Impact Green Ecological*	*Central sterilization Central sterile Sterilization Washing and disinfection Decontamina Steam sterilization Autoclave Autoclaving*	*Hospital Medical clinic Clinic Healthcare Health care*	*Water Waste water Valuable water Washing water Effluent Waterflow Continuous -water Continuous flow*

Fig. 2. Broader version of concepts used in Scopus for using in the second search query to finding relevant articles to answer sub question 1

C. Final Search

The second search will contribute of the extended list of concepts seen in figure 2: **TITLE-ABS-KEY** *(environmental footprint)* **AND** *(Department)* **AND** *(location)* **AND** *(Medium)*.

The whole search query in Scopus is: **TITLE-ABS-KEY** ((”Carbon emission” **OR** ”environmental impact” **OR** ”operational emission” **OR** ” Greenhouse ” **OR** ”medical waste” **OR** ”sustainability” **OR** ”sustainable” **OR** ”environmental” **OR** ”Life cycle” **OR** ”footprint” **OR** ”energy consumption” **OR** impact **OR** ”green” **OR** ecological) **AND** (hospitals **OR** ”medical Clinic” **OR** ”clinic” **OR** healthcare **OR** ”health care”) **AND** (”central sterilization” **OR** ”central sterile ” **OR** autoclave **OR** autoclaving **OR** sterilization **OR** ”washing and disinfection” **OR** ”washer disinfectant” **OR** ”decontaminate” **OR** ”steam sterilization”) **AND** (water **OR** ”waste water” **OR** ”valuable waste” **OR** ”valuable water” **OR** ”washing water” **OR** effluent **OR** sewage))

This resulted in **267** documented to be scanned for **87** titles seems promising to read the abstract. For an overview see figure 6.

Another search in google scholar is done as well. This ((”Carbon emission” **OR** ”environmental impact” **OR** ”footprint” **OR** ” Greenhouse gas”) **AND** (”steam sterilization” **OR** ”central sterilization” **OR** ”central sterile ” **OR** sterilization **OR** autoclave) **AND** (Water **OR** effluent)) this resulted in **34.900** results GS is set to order the results in a most relevant matter. The first 25 pages are read through 250 articles and **21** titles seems promising for reading the text and abstract about **6** articles seem to provide additional information but **4** of the articles were already found in the Scopus search.

The exploring search combined with the final search will result in a total of **120** abstracts to be read. With help of the inclusion and exclusion criteria stated in subsection III-B, **36** articles in total can be scanned for a future readings and improvement for the final search. These articles are also checked for potential snowballing effect and an addition of **4** articles seem to have new information listed. Eventually a total of **20** articles seem to have unique information that can be combined to answer this research question. During the scanning of the complete literature reviews it was noticed that Rizan and McGain were researchers that did its research in the direction that this literature review also was looking into. Thus their names were searched in Scopus to perhaps find more relevant articles this resulted in an addition of **2** articles.

IV. Literature search II: Water Heat reclaim systems

As already stated in chapter II the initial sub question to find information about is : **What methods are available to use energy lost by means of reusing the heat in water?**

During the initial search session the sub question is adapted to :**What methods are available to decrease the amount of energy lost as effluent heat by means of reusing the heat left in water?** The sub question is altered due to a more precise definition of where the energy is lost. This should help to narrow the search results down to find the best literature about the subject.

The first steps taken in this chapter is to set up a proper search query, this can be read in subsection IV-A. After the search criteria is setup all the titles and abstract must fulfill the inclusion criteria stated in subsection IV-B. During the check of the inclusion criteria additional keywords are found and included into the final search in subsection IV-C

A. Initial Search

As already stated in subsection II-B the sub question can be derived into concepts. The initial concepts with the subjects can be found in figure 4. To gain the subjects, synonyms for the concepts need to be sought, this is done with help of *www.thesaurus.com* [10] the great advantage of this site is that the site not only finds the exact synonyms but also gives words that do not mean exactly the same and the site color code these words on the amount similarity of meaning. These synonyms will be combined with the word **OR** and the different concepts will be combined with the word **AND**. The ”” in for example ”Tube heat exchanger” are used to search on the word *Tube heat exchanger* and not on *tube* **AND** *heat* **and** *exchanger*. In Scopus it is an option to only search in the title, abstract and the keywords this function (**TITLE-ABS-KEY**) is used in all searched to decrease the amount of results. This is done because Scopus will find the words throughout the whole text even if the subject is listed just once.

The first query that is used to find information is as follow, the subjects of the concepts can be seen in figure 3: **TITLE-ABS-KEY** (*(Heat Exchange Mechanism)* **AND** *(Medium)* **3.100** results can be found. To decrease the amount of literature to the desired category it is chosen to limited the search to: *Applied Thermal Engineering and International Journal Of Heat And Mass Transfer* this will give **404** documents to be read. It is noticed that a rather large portion of the results given were focusing on either Nanofluid, condensation and evaporators and latent heat. These subjects were combined with the **AND NOT** function to exclude them from the search query. This resulted in a total of **301** articles to be read. After all the titles of the articles were read and compared with the inclusion criteria **112** promising title are left. Of all these titles all the abstracts are read and about **16** abstract are found to be promising for relevant information to answer the sub question.

To increase the amount of articles the first **150** titles of articles on GS with the search query : (”shell heat exchanger” **OR** ”tube heat exchanger ”**OR** ”thermal heat exchanger” **OR** ”shell and tube heat exchanger” **OR** ”plate heat exchanger”) **AND** (water **OR** liquid **OR** fluid) **AND** (Recover **OR** Reclaim **OR** reheat **OR** conservation) and sorted by relevance are a read through. The reading of the tile resulted in an additional **30** relevant articles, unfortunately **21** of these articles are already found on Scopes. After all the abstract of the **121** documents were read through. Only **19** documents seem to be use full for scanning of the whole texts, for a complete overview see figure 7.

While looking through through the keywords of the to-be-read articles it was noticed that some included the term of reuse or similar. This keyword and similarities are included in the final search for the literature review.

	Combine concepts with AND			
	Heat Exchange Mechanism	**Medium**	***AND NOT***	***Limit to***
Combine concepts with OR	*Tube heat exchanger* *Plate heat exchanger* Shell heat exchanger *Thermal heat exchanger* *Riotherma*	*water* *liquid*	*Latent* *Nanofluids* *Nanofluid* *Vapor* *Conden*	*Applied Thermal Engineering* *International Journal Of Heat And Mass Transfer*

Fig. 3. Initial list of search subjects used in Scopus for finding relevant articles to answer sub question 2.

B. Inclusion And Exclusion Criteria

For subquestion 2 the *inclusion criteria* that are mentioned in the title must contain both of the following criteria:

- Heat exchanger
- Fluids or synonym

And the *exclusion criteria* are that should not be mentioned in the title are:

- Fluids with a 1.5 times higher viscosity as water.

For subquestion 2 the *inclusion criteria* that are mentioned in the title must contain two of the following:

- Heat exchanger
- Analyzing/ modeling/ design / experiment/ study
- Fluids or synonym

And the *exclusion criteria* that should not be mentioned in the title are:

- Fluids with a 1.5 times higher viscosity as water.

C. Final Search

The final search query for **subquestion 2** can be seen in figure 3 and is as follow:

TITLE-ABS-KEY (*(Heat Exchange Mechanism)* **AND** *(Medium)* **AND** *(Reusing)* **AND NOT**).
The search quarry that is used in Scopus is: **TITLE-ABS-KEY** ((”tube Heat exchanger” **OR** ” plate and frame heat exchanger” **OR** ”Plate-and-frame heat exchanger” **OR** ”plate heat exchanger” **OR** ”shell heat exchanger” **OR** ”shell and tube heat exchanger” **OR** ”riotherma” **OR** ”energy rewinning” **OR** ” thermal heat exchanger”) **AND** (recover **OR** reuse **OR** reclaim **OR** conservation **OR** salvage **OR** preheat **OR** reclaim **OR** Reheat) **AND** (liquid **OR** water **OR** fluid) **AND NOT** latent **AND NOT** nanofluids **AND NOT** nanofluid **AND NOT** vapor **AND NOT** conden)

This resulted in **257** articles where all titles were read. After reading the title **75** abstracts were left to be read this resulted in **50** articles to be scanned for useful information. The useful articles **24** found in the final search are combined with the search results of the initial search. This combination resulted in a total of **30** useful articles. While scanning through the total of **30** articles **4** new articles were found with help of the snowballing technique. An overview can be seen in figure 8

It is chosen not to implement a search query in GS because it was noticed that during the initial search a lot of duplicate articles were found. With the already **12** useful papers found in subsection IV-A the addition information that could be provided by google scholar seems to be minimal.

	Combine concepts with AND			
	Heat Exchange Mechanism	**Medium**	**Reusing**	***AND NOT***
Combine concepts with OR	*Tube heat exchanger* *Plate heat exchanger* *Plate-and-frame heat -exchanger* *Plate and frame heat -exchanger* *Shell and tube heat -exchanger* Shell heat exchanger *Thermal heat exchanger* *Riotherma*	*Water* *Liquid* *Fluid*	*Recover* *Reuse* *Reclaim* *Conservation* *Salvage* *Preheat* *Reclaim* *Rewinning* *Reheat*	*Latent* *Nanofluids* *Nanofluid* *Vapor* *Conden*

Fig. 4. Final list of search subjects used in Scopus for finding relevant articles to answer sub question 2.

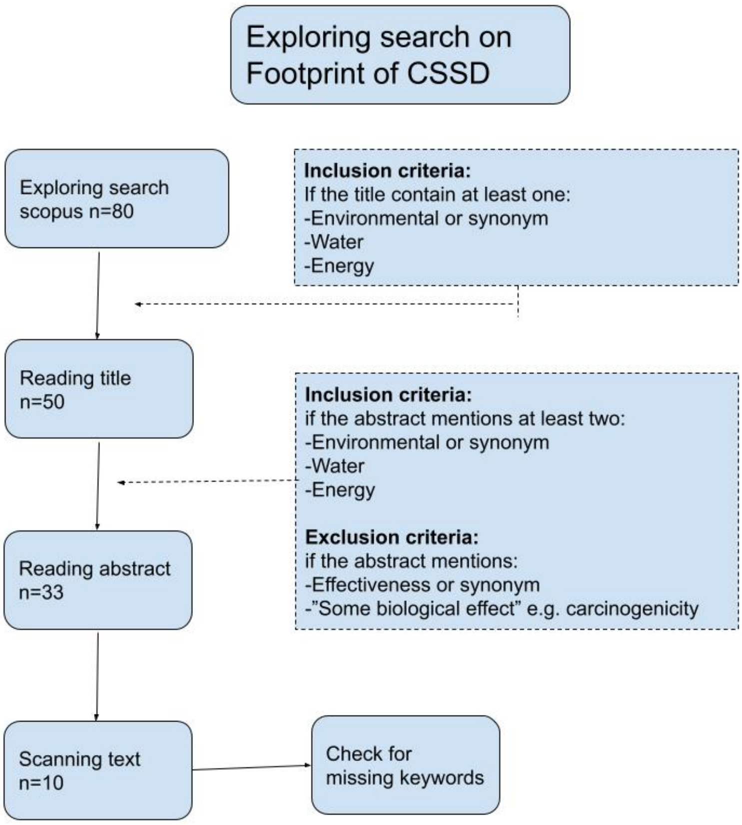

Fig. 5. Diagram of the exploring search on the CSSD.

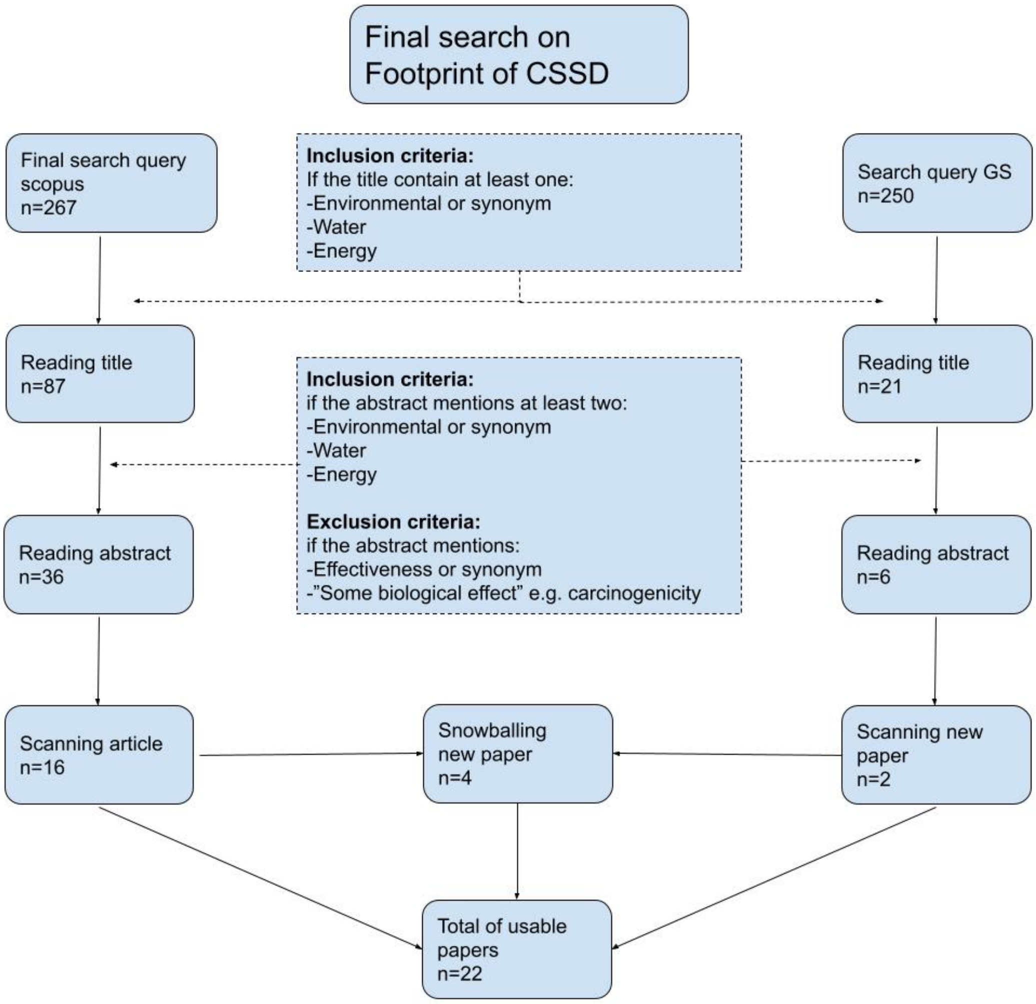

Fig. 6. Diagram of the final search on the CSSD.

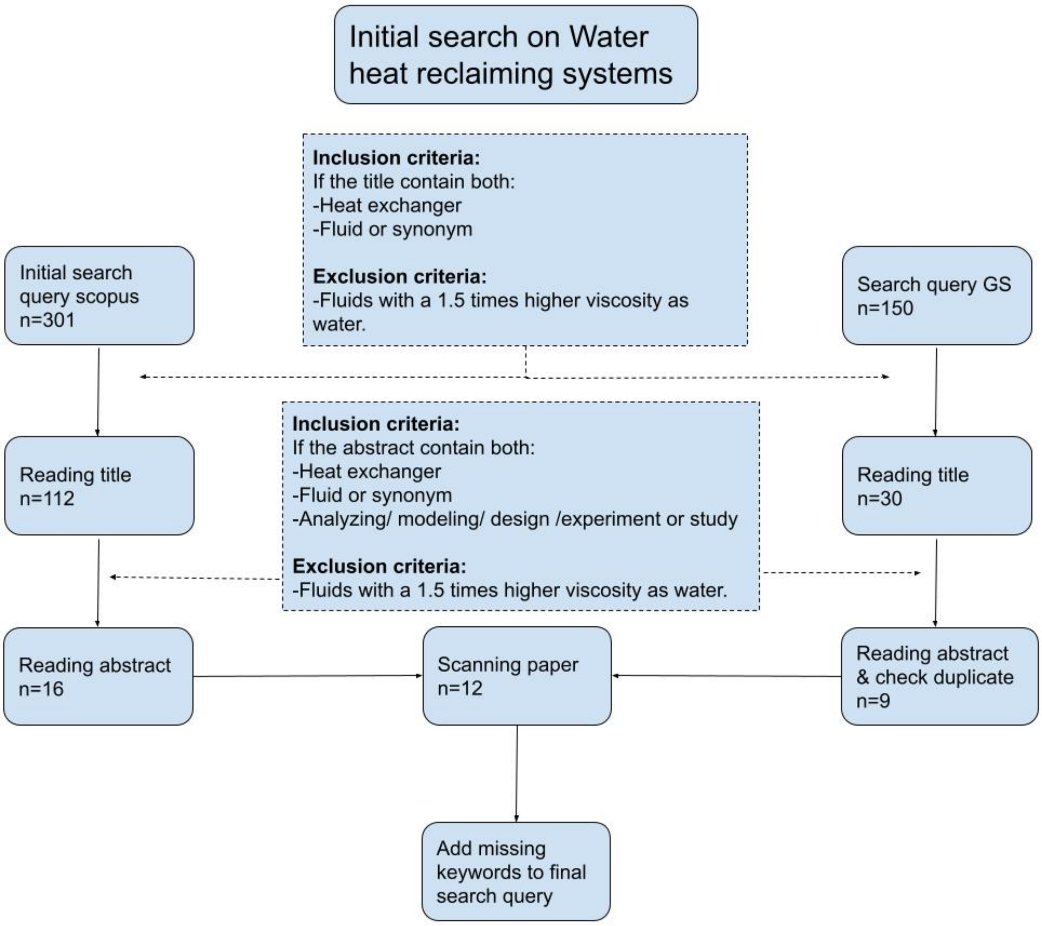

Fig. 7. Diagram of the exploring search on HEX.

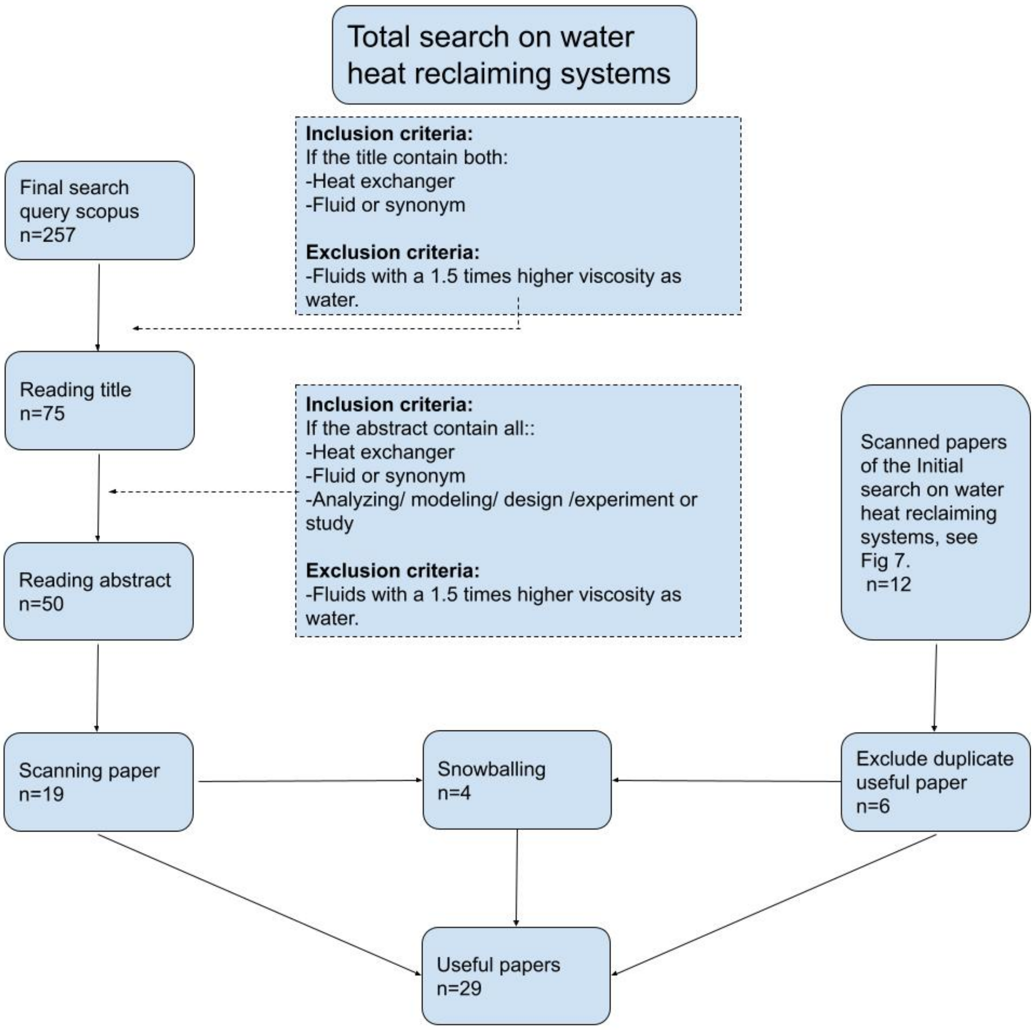

Fig. 8. Diagram of the final search on HEX.

V. RESULTS CSSD SEARCH

Climate change will decrease the quality of the earth and this might introduce health problems for the inhabitants. Luckily for these sick people, hospitals will provide care for them. Unfortunately the hospitals produce massive greenhouse gases like CO_2 [16]. The healthcare sector of the US in 2016 contributed to 10% of total CO_2 emission in the United States and produce approximately 655 million tones CO_2 per year [3]. The healthcare in the united kingdom (2022) is responsible for 7% of their total CO_2 emission [2].

In the hospital one of the major electricity consumption department is the operation theatre and the sterilization units, combined they consume between 10% and 25% of the energy used at a hospital [4]. According to Thiel et al. (2015) [17] the operation theatre has the highest energy consummation of both hospital departments. In the literature it is noticed that about 12 % of total energy consumption and 31% of gas use of health care clinics is designated to hot water production [18] The hot water production by the boilers is used for several different departments like laundry, kitchen and the CSSD . Unfortunately the article does not distinguishes the consummation of gas between these departments in the hospital. According to a research done by Stanford Hospital in 2012 [19], the water resources used per individual in a hospital varies between 150 litres and 1300 litres. The largest consumer of water is the sanitary area and about 20 percent of total water consumption is used during the sterilization process

The CSSD main task is to clean and sterilize medical instruments to be safe for use during operation. Single use instruments will only be used a singe time as opposed to reusable instruments whose lifetime, dependent on type of instruments, sterilization can vary between 40 [20] and 4500 [23] uses.

There are number of ways to sterilize instruments, the most common used method is to use steam. Unfortunately, this steam sterilization is not the most environmental friendly sterilization technology in comparison to for example radio-wave sterilization. Nevertheless, steam sterilization was the first and currently the most used method to sterilize. Water consummation of a steam sterilization in the research of Mitchell et al. (2022) [25] consumes about 5400 L of water per day. The 5400 L of water a day is used for the creating of steam and the condensation of steam for save drainage during the idling phase and the active sterilization phase. The capacity of a steam sterilization is normally noted as volume of the cavity of the machine and is listed as full when no additional tray can be inserted into the machine. For an overview of the information found on the autoclave and washer disinfection machines see table 2.

Washer disinfection machine: The heating of the water in washer disinfection machines usually happens at the underside of the machine inside the cleaning chamber, where the washing fluids is collected as well. The water in this rump is reused and pumped through the machine during a certain cleaning phase. If the cleaning phase is ended the water will be pumped into the drain and new clean water is tapped into the rump to be heated again. The maximum temperature in the disinfection phase is 93 degree Celcius.

Autoclave: Autoclave machines will use steam to sterilize the products. The steam is provide by heating water up to 140 degree Celsius. When sterilization is finished an exergy destruction valve in combination with cooling water will cool down the medium and thus provide possibility for the steam to change phase into liquid. This liquid will be drained away into the sewage.

In the literature a lot of research is done on decreasing the amount of carbon emission of the CSSD [26], [27], [28], [29], [30]. Thorough research that summarizes the option for lower carbon emission of the CSSD is Mitchel et al. (2022) [25]. In this research it is stated that one simplistic solution to decrease the energy waste from the sterilization machines is to upgrade to newer more efficient ones. The new sterilizer and washer-disinfect could save up to 45 million liters of water according to a case study at Stanford hospital [19] another simplistic option to decrease the amount of water consumption and CO_2 production per surgical instruments is to use less instruments. Another simplistic approach to limit the carbon emission of the washing machine and sterilizer is to just turn them of [26].

During the pandemic of Covid research by vanStraten et al.(2021) [7] was done to investigate the possibility to re-sterilize face masks up to 5 times. The ecological conclusion that was taken is that if the face masks were re-sterilized the sterilization process would account for 30% of the total CO_2 emissions already.

Rizan et al. (2022) [20] estimates that around 364 million reusable scissors are used each year. The disinfection of reusable scissors, with repair not in house, contribute to 76% of CO_2 emission. While the decontamination contribute to 95-96% of CO_2 emission for reusable instruments after 40 uses without repair. The total cost per surgical reusable surgical scissors comes to a total of 0.97 pounds per scissor. With help of different literature [31] about reusable trocars up to 500 times reusable the allocated cost for the sterilization machines represented 12% of the total cost.

Another research of Leiden et al.(2020) [21] states that sterilization and decontamination of a life time use (300 times) of spinal fusion surgery equipment contribute between 80% and 90% of total carbon emission. A lifecycle assessment is done by Davis et al(2018) [22] in which the study looked at the CO_2 emission of a life time use (180 uses) of endourologic cases. During this research it was stated that out of the 4.47 kg CO_2 emission a total of 3.95 kg CO_2 was produced by the sterilisation department. Thus 88% of the CO_2 emission of 180 uses of endourologic cases is from the sterilisation. For an overview of all the medical devices and the carbon production in regards with sterilization and cleaning can be seen in table 3.

In one of the researches done by Rizan et al.(2021) [32], about the contribution of CO_2 emission per consumption of power they established during this research that about 92% of total emission during the cleaning phase comes from the use of gas.

Mcgain et al.(2012) [13] stated that it should be kept in mind that while estimating the amount of CO_2 emission the source of power need to be specified. For example the electrical power plants in Australia commonly uses brown coal as main fuel, while electrical power plants in America and Europe do not use brown coal as main fuel but more renewable sources thus the CO_2 production of researches done in America or Europe would have resulted in approximately 33% and 50% less CO_2 emissions.

Ibbotson et al. (2013) [23] did a research on the total electricity consumption between single use stainless steel surgical scissors and reusable stainless steel surgical scissors. The lifetime of the reusable scissors is estimated at 4500

Source	Author	Device	Cold water (L)(13 °C)	Warm water (L)(°C)	Hot water (L)(90 °C)	Gas consumption (kWh)	Electricity consumption (kWh)	Total water consumption (L)	capacity in volume (L)
[12]	Adler et al (2004)	Miele G 7736 CD MCU (labsize)	112	15 (45 °C)	49	-	3.8kWh	176	150
[13]	Mcgain et al (2012)	-	126	79 (65 °C)	-	7 kWh	4.1kWh	-	-
[14]	Rizan et al. (2022)	Steelco TW300/3	-	?(65 °C)	-	3.9kWh	8.17 kWh	255	500
[15]	Steelco	steelco	0	400 (55 °C)	80				
[16]	McGain et al(2017)	Electric autoclave	500	0	30.3 (134 °C)	-	22.3 Kwh	530	
[14]	Rizan et al.(2022)	v9935 BM Weston (Autoclave)	-	-	-	46.28	4.27 Kwh	760	1200

TABLE 2. WATER CONSUMPTION OF WASHER DISINFECTS MACHINES AND AUTOCLAVE.

cycles, this resulted in a contribution of electricity uses by the sterilisation process of up to 85 %. Of these 85%, 81% of this electricity was used for the production of steam. According to lemonnier et al. (2019) the heating of water in for washing, disinfection and sterilization in the CSSD contribute to 73% of carbon emission in that department.

In a study done in the UK by Byrne et al.(2022) [24] for the NHS about reusable or single use dental examination kit. The reusable kit can be reused for 250 times. It is concluded that there is a significant less material and energy needed when there is chosen to make use of reusable examination kits in contrary to single use kits. The sterilization process will contribute to between 64.8% and 85.1% of the carbon emission. The range of carbon emission is due to the endpoint of the research the lower 64.8% does account for the landfill and reprocessing of the instrument.

Sahin et al(2022) [33] states that even though the autoclave in this study is isolated with a double walled boiler. The heat lost of the total sterilisation cycle is about 10% most of this lost is due to radiation of a heated surface of the machine. Also in this study it is concluded that the water(steam) inlet for the sterilization phase is 130 degree Celsius and the outlet of the water is about 95 degree Celsius. A lot of this heat is lost due to exergy destruction.

Adler et al (2004) [12] has done research on ecological and environmental impact on reusable instruments used during laparoscopic cholecystectomy. Special consideration for the washer disinfection and its cost and consumption is given the washer disinfection machine used in this research is the *Miele G 7736 CD MCU*. This washing machine is a laboratory size washer disinfection machine and only consist of 2 washing racks [34]. The energy and water consumption was measured with help of water flow measure and power measurement tools. The prerinse program uses 112 liters of cold water to rinse the 2 washing racks within the machine. this is followed by a cleaning phase of 15L of warmer water sprayed at 45 degree Celsius. The final rinse contribute of 49 liters of desalinated water for at least 10 min for 94 degree Celsius to thermal disinfect the instruments in the tray. The total electrical energy consumption is 3.8 kWh. Also the cost per sterilization is approached to approximately €0.95 euro per sterilization (with packaging, repair etc) of a laparoscopic cholecystectomy equipment. A total cycle will cost about €2,80,- per load which €0,41 is from heating of water.

In a study done by Mcgain et al.(2012) [13] the CSSD staff estimated that on average 90% of the capacity of the washer was used. The washer will use 126L of cold water for the prerinse of the instruments and uses 7kWh gas to heat 79L the water for the cleaning phase (65 degree celcius). The washing machine also uses 4.1 kWh of electricity per load. The operation consumption of the sterilizer is also tested, this shows that per load 22.3 kWh is used and about 500 L of water and 30L of steam.

Mcgain et al.(2017) [16] logged an unkown hospital steam steriliser's in Australia. Over a period of 304 days the researchers have counted 1343 full cycles of both the autoclave operations and washer disinfection operations. The consummation of electricity energy was measured to be 33 Mwh and a total water consumption of 1 243 cubic meters. In the article written by Mcgain et al. (2017) [16] it stated that 40% percentage of total energy was lost due to apparatus in stand-by state.

In a study conducted by Rizan et al(2022) [14] it is estimates that the CO2 emission due to washing and decontaminating is between 66 and 190 g CO2 per medical scissor. The washer disinfection machine used in this study is a TW300/3 fabricated by Steelco. The total input for decontamination in this study is 8.17 kWh electricity. A total of 255 liters of water is used during the prerinse, cleaning and thermal disinfection stage. The boiler will heat a part of the water and uses 3.9 kWh gas to get the water up to 65 °Celcius for the cleaning phase and 95 degree for the thermal disinfection phase. The power, gas and water consumption combined to a total CO2 emission of 3.74 kg CO2 per load. The steam sterilizer(v9935 BM Weston) used in this research consumes 4.27 kWh of electricity and 760 Litres of water and steam to heat the water up to steam the boiler uses 46.3 kWh of gas. With all the consumption of the steam sterilizer combined a total of 12.13 kg CO2 emission per cycle is produced.
The steelco TW300/3 washing machine has an inbuilt thermal energy recovery system, thus the gas consumption is much lower due to a preheating tanks which will reuse the heat left in the effluent. This reheater decreased the gas usage tremendously. This device is approximately 3 years old and shows the relevant development in this industry and shows the possibilities to implement a relative cheap heat exchanger in old devices .

Source	Author	Device / Type of surgery	# Of usage	Total kg of CO2 emission	Percentage CO2 emission due to cleaning	kg Of CO2 emission due to cleaning
[7]	vanStraten et al. (2021)	Face masks	5	2.86	30%	0.83
[20]	Rizan (2022)	Medical Scissor	40		76%-96%	
[21]	Leiden et al.(2020)	Spinal Fusion	300		80%-90%	
[22]	Davis et al (2018)	Endourologic Cases	180	4.47 kg	88%	3.95 kg
[23]	Ibbotson et al. (2013)	Surgical scissor	4500		85%	
[24]	Byrne et al. (2022)	Dental examination kit	350		64.8%-85.1%	

TABLE 3. OVERVIEW OF THE PERCENTAGE OF CO2 EMISSION DUE TO STERILIZATION OF DIFFERENT MEDICAL EQUIPMENT DURING THEIR TOTAL LIFE SPAN.

VI. Results HEX

In a research done by Selcuk et al.(2021) [35] One simplistic plate heat exchanger of 87,- placed in the effluent of shower water will recover up to 27% of the heat. This heat will be used to preheat the cold water of the shower and establish a payback period of 2 years. This potential heat recovery mechanism should be applied to the medical washers as well. The goal is not only to save money due to using less gas to heat the water but also to decrease the CO2 emission of the sterilisation services. On a bigger scale, a study is done by Kosek (2008) [36] for a commercial laundromat in the study it is stated that a recovery of heat in wastewater can extract about 50% to 75% of the energy. This would reduce the gas needed to heat the water by a maximum of 21%. The effluent of the washer disinfection machine still has high potential energy left in the form of heat. It is wishful to extract this heat to preheat the new water that is needed for the next cycle. The implementation of heat exchanger is not new, but the amount of useful applications can be increased massively. Especially now that the price of gas and electricity is increased over the last two years and the break even point of investment might be reached in a shorter period of time which will be a positive point of investment for the machine.

According to a research done by Master et al. (2007) [37] there are two different kind of heat exchangers that are used most, the tube-shell heat exchanger and the plate heat exchanger. This is in agreement with the book of Hall [38]. In which it is stated that there are three types of heat exchangers commonly used worldwide in industry. The shell and tube heat exchanger, plate heat exchanger and the spiral heat exchanger.
The tube heat exchanger is often the lowest cost option and most suitable of liquid-liquid heat exchanging. There is a large amount of iterations possible on the designs of tube and shell heat exchangers. On the other hand Plate heat exchangers or sometimes referred to as plate-and-frame heat exchangers can be advantageous over tube and shell heat exchangers due to its compact design and sometimes a higher heat coefficient then tube and shell heat exchangers. A high shell side velocity can be advantageous to increase efficiency of heat transfer. The spiral heat exchangers on the other hand is commonly used for slurry's and will thus not be taken into account in this review due to a higher density of fluid. This resulted in the choice of reviewing more about the two major used heat exchangers worldwide.

- Plate heat exchanger, see subsection VI-A
- Shell and tube heat exchanger, see subsection VI-B

.

Fouling of particles is a major hazard for the efficiency of heat exchangers [39]. The fouling of particles is the build up of material like: bacteria, salts or residue to the walls of the heat exchanger. The layer of this residue can grow up to 0.5mm in three months [39], fouling can occur on all kind of heat exchangers. The amount of fouling due to micro-sized particles located in the viscous- sub layer of turbulent flow is majorly dependent on the flow velocity. There is an equilibrium of flow velocity to have a balance between the size of micro particles and the amount of particles fouling to the surface. In a low flow velocity the size of particles will increase but the amount of particles will decrease. If the flow velocity is higher the particles sizes will decrease but the amount of fouling will increase [40]. Particle detachment can occur as well, there existing only one theory about particle

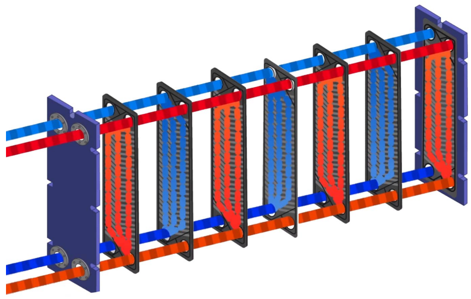

Fig. 9. Working mechanism of a plate heat exchanger. [44]

detachment and it's written by Cleaver and Yates in 1973 [41] they state that the detachment will happen randomly due to random changes in the turbulent flow. Fouling can also have a beneficial effect on initial low flow heat exchangers. This positive effect will decrease with a higher flow or a longer period of time. [42] Another important characteristic for the efficiency of thermal heat transfer is the pressure drop that can occur. A high turbulence flow typically means that a high pressure drop occurs [43]. This pressure drop need to be compensated by usage of a pump to keep the fluid flowing. Therefore a balance between turbulence and the pressure drop need to be taken into account while designing. A fully complete turbulence flow means that the Reynolds number is typically above 4000.

Re= ρ * v* D/ μ

With ρ = density of the fluid [kg/m^3]
v= velocity of the fluid [m/s]
D= hydraulic diameter[m]
μ = viscosity of the fluid[kg/(ms)]

The Reynolds number can be seen as the amount of movement in a flow. Thus the amount of mixing of the hot or cold water on the rim after heat is exchanged with the fluid outside of the tube. Reynolds number is dependent on the velocity, density and viscosity of the fluid, and dependent on the diameter of the tube it flow through. See the formula above. The placement of the pump before or after the heat exchanger will also influence the efficiency of the heat exchanger. The pump is needed to overcome the pressure prop in the heat exchanger. According to a study by Shen et al. (2014) [42] the placement of the pump before the heat exchanger will result in less power needed to compensate for the pressure drop during heat exchange.

A. Plate heat exchanger

Plate heat exchangers are adjacent plates that can be soldered, welded or brazed together or being tightened with a gasket in between the plates are fasten with help of a bolt and nut. The plates will provide a barrier between the two fluids and the corrugation in the plates will result in turbulent flow. A great advantage of the plate heat exchanger is that it is rather compact and will provide high efficiency over low temperature difference between the two fluids. [45] [43].
Another great advantage of the Plate heat exchanger is its compactness and for the bolt and nutted type the ability to be cleaned. On the other hand the bolt and nutted type is more prone to leaking then the welded type which is not cleanable

that easy. The plates in a bolt and nutted type can also be increased or decreased by simply inserting or extracting a plate in the heat exchanger.

A plate heat exchanger(PHE) can be seen in figure 9. Major parameters important to the total efficiency of a PHE is the chevron angle of the herringbone, the corrugation of the bumps to create the herringbone and the surface roughness of the plate [46]. All these aspects will increase the Reynolds number and thus the turbulence. The tasks of the chevron angles is to divide the fluid over the whole surface of the plate [47]. These chevron angles are corrugated to establish an forced zigzag flow of the medium. The surface roughness will induce additional turbulence.

Surface roughness is one of the influential aspects of the efficiency of plate heat exchanger. A research done by Lyytikäinen et al. (2009) [48] noticed that during their experiment on corrugated plates with symmetrical chevron angles of 25 degree with surface roughness between 0.956 μm and 3.312 μm. The efficiency of heat transfer increased between 5% and 18% but this induced also an increase in pressure drop that should be overcome by using a pump. Another research about the surface roughness and its influence on the heat transfer coefficient is done by Nilpueng et al. (2018) [49]. In this research the chevron angles of 30 degree and 60 degree with several different surface roughness were studied. It was noticed that an decrease in chevron angle would increase the efficiency but this also causes an higher pressure drop. So an optimal chevron angle and surface roughness was found at 30 degree and 2.77 μm.

There is much research done [45], [50] over the last eighty years but this has not resulted in a load of design information in the open literature. There is some standardised method available for limited geometry, operation condition and certain fluids. The restricted mythology is reached by using empirical and theoretical correlations and some model predictions. One of the methods used to gain knowledge about the specific heat transfer correlations is the Wilson plot [43], [49]. This Wilson plot will provide information with the input of experimental information about the heat transfer coefficients. A design tool that can help the designing of heat exchanger is a simplified 3D model into a 2D model [51]. A 3D geometry render can take up to several hours to complete, while on the other hand a simplified 2D model can be rendered in a couple of minutes. Even though the depth is loss due to the simplification the 2D model have an good accuracy in contrast with the 3D model. This 2D model can increase the speed for the rough estimation of the apparatus in the first stage of development.

Untreated 90% of the Plate heat exchangers will suffer efficiency decrease due to fouling. With help of a PWT coil and filter the fouling will decrease up to 72% according to Zhang et al. (2013) [52]. A 30 degree chevron angle structure of corrugated plate should have a higher capacity of resistance against fouling then a 60 degree chevron angle structured plate [40].

B. *Shell-tube heat exchangers*

A shell-tube heat exchanger is build up from a few important parts that determine its efficiency. The outer area of the heat exchanger better known as shell will provide a box for the hot water. The to be heated fluid will flow through the tubes that are hold in place by the baffles. An important function of the baffles is to blocks the straight flow of water

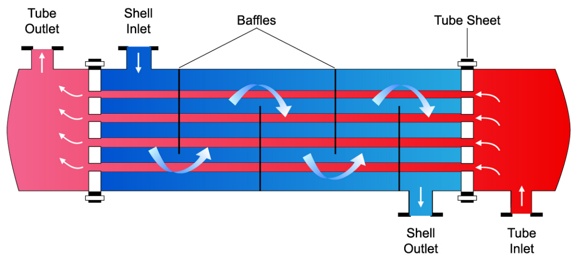

Fig. 10. Working mechanism of a shell and tube heat exchanger. [58]

to introduce turbulence. This baffle dimension have a high influence on the total thermal heat transfer coefficient [53]. The total thermal heat transfer coefficient depends on three parts [54] : the shell-side heat transfer coefficient, the thermal conductivity of the tube wall, and the tube-side heat transfer coefficient. A few typical efficiency killers for the shell-tube heat exchangers are flow dead zones behind baffles and high pressure drop. The role of baffles is to support the tubes and create turbulent flow, baffles spacing and orientation is one of the most important design aspects of this type of heat exchanger [55], [56], [57]. Due to the turbulent flow the Reynolds number increase and this will increase the heat transfer coefficient and the pressure drop. It was noticed during an experimental research done by Singh et al. (2013) [57] that when the baffles are inclined increasingly in each experiment from an angle between 0 degree and 60 degree that the turbulence increased thus resulting in a higher heat transfer. Unfortunately the extra turbulence, increase in Reynolds number, create a need for more pumping power to overcome the pressure drop. An important aspect of the baffles angle and distance is the amount of fouling it induces, an optimal geometry should prohibit the amount of fouling produced [39].

Chen et al. (2021) [59] have investigated the influence of segmented baffles on the thermal transfer coefficient. One of the founding stated in this literature was the 40 degree angle of baffles that resulted in the highest efficiency. Another point of interest in this research was the so called segmented flower baffles. In a typical ordinary shell-tube heat exchanger the baffles will alternate placement on the top and bottom part of the shell and result in a zigzag flow of the medium. The segmented flower baffles consisting of three segments will drastically increase the turbulence flow due to adjusting the zigzag flow in a more random pattern. This random flow will also decrease the pressure drop in the heat exchanger and will decrease the dead zone at the back of the baffles which is a common place for fouling in shell-tube heat exchanger.

In a research done by Abbasian et al. (2019) [56] about different designs of shell-tube heat exchangers. The designs that were compared with use of a simulations in solidworks consisted of different kinds of segmented baffles and shapes of tubes. The discontinuous baffles Triangular rib(DB-TR) have shown the best configuration. 40 Degree inclination of the helix baffle should have the highest efficiency according to the study of Gao et al.(2015) [27]. The outside shape (addition of a rib) of the tube have a high effect on the increased efficiency of the heat exchanger. The rib not only provide additional surface area due to the extra rib but will also provide more turbulence [56]. Fetuga et al. (2023) [50] shows as well that if a triangular beam in longitude direction is added the efficiency of heat transfer increases in comparison with no adjustment of a round tube. In the experiments done in this research it shows that 35 degree of baffle have the highest efficiency due to least pressure drop and high thermal transfer coefficient.

To evaluate the total heat transfer, in the literature empirical research is done most of the time. This gives a good view of the total heat transfer but not of the three components. According to Wang et al. (2019) [54], the tube wall thermal conductivity is mostly known and with help of the empirical data the shell-side heat transfer coefficient and the tube-side heat transfer coefficient can be calculated. It is also possible to design a shell-tube heat exchanger with the help of the Kern method. The Kern method [55] is only suitable for predetermined dimensions and gives only rough results. Another more detailed method to design a tube-shell heat exchanger is the Bell-Delaware method [60], this method is very accurate in guessing the pressure drop and shell side heat transfer coefficient but need empirical input.

VII. Discussion

In this section a discussion can be read on the found articles. Firstly the database used for finding of relevant papers will be discussed. Secondly the timeline of most articles will be shown. Thirdly the most top authors that are found will be discussed. Finally a short (subjective) discussion on the content of the articles will be given

A. *Discussion found articles*

For this literature review over 50 articles are read and used to gain information to answer the main question. 26 Of this articles were used to gain information of the carbon emission, water, gas and power usage of the CSSD. 28 Of the articles found were used to gain information of the heat transfer systems.

It became clear that for the CSSD articles, that a large portion of the articles published were about autoclaving waste for save reprocessing. Even though these articles were not immediately helpful to answer the main question. It was decided not to excluded them in the inclusion and exclusion criteria due to the hope of information provided for the CO2 production of the machines, unfortunately this was not the case.

As discussed in VII-B the information of water consumption of washer disinfection and autoclave machines was limited. To gain more information, a search is done at Espacenet [11] which resulted in only one additional informative article. It was hoped that the first search, see subsection III-A, resulted in information about the washer en autoclave machines itself. When this information was not found solely the search was a bit broaden to try to get this information with help of the reusable versus single use instrument debate. It was found that most articles used an existing database Ecoinvent, which database I could not use because I did not have any access. The amount of articles to show the impact of CO2 production of sterilization on the total impact of reusable instruments were clearly shown by only using 6 articles. I think due to the fact that research on the CSSD might be interfering with the health of people and regulations, the results on this particular research are limited.

It was also noticed that the search on Google Scholar gave relevant articles for the first ten pages or so. Which were mostly already found on Scopus. So I would suggest to only use Google scholar as initial search due to the great relevance in the first few pages.

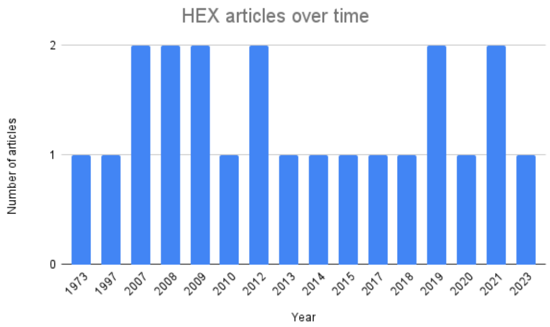

Fig. 11. HEX articles over time

For the search query of heat exchanger it was decided not to include the term *heat exchanger* because this resulted in additional 10.000 articles. It was therefore firstly decided which heat exchangers were commonly used and therefore needed more attention. This limited the search and results to a manageable proportion. It was noticed that the term *Fouling* was used in a lot of titles of articles. Therefore, some research about fouling was conducted as well. A lot of research on improving both type of heat exchangers were done in the last years. The plate heat exchanger usually can be modified with a limited amount of possibilities which resulted in a good comparing between the found articles. While on the other hand the shell and tube heat exchanger can be modified in almost limitless possibilities. Resulting in a very broad amount of articles discussing different setups. A few articles are chosen to compare their results even though the boundary conditions are not similar. As the concept of heat exchangers is already studied for several tens of years there is no specific researcher or time period noticed in figure 11.

It was noticed during research that the relevant articles found in the context of CSSD were relative new, approximately 10 years old. This can be confirmed by figure 12. What is noticed in this figure as well is that a load of relevant articles is written in the year 2022. According to the national center of environmental information [61] in the year 2021 a lot of worldwide environmental records were broken, in combination with the Covid pandemic and the debate of the footprint about the pandemic. Both facts could have increased the total articles about carbon emission of the sterilization units this could have resulted in the high amount of articles in 2022. The start of most articles are from the year 2012 and onwards.

During scanning of the articles it was noticed that C. Rizen and F. Mcgain were cited, in this paper seven of their articles are cited. Rizan, especially the article of 2022 [14] is one that I found that did really investigate the consummation of washing and autoclave machines with help of power measurement and described them instead of using databases. McGain also did research on the washing machines and autoclave machines with power measurements and described them. An useful article written by Mcgain in 2017 [16] is a year long observation of a CSSD unit, which is unique. Both C. Rizan and F. McGain started to write their first environmental literature around the years of 2010 while they both started their career focused on other aspects.

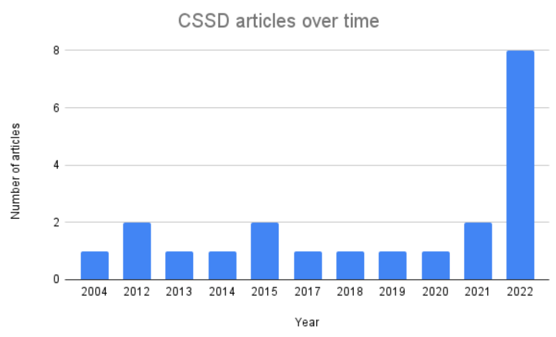

Fig. 12. CSSD articles over time

In figure 8 it can be seen that 29 useful papers are found. Even though only 28 papers are used and cited, this is because the broadness of the search resulted in broad articles which sometimes were not possible to connect them to other articles or were just eventually outside the scope, even though they looked very promising during scanning.

B. Discussion on content

A short subjective review on the content of the articles will be given in this section.
During the research it is noticed that a lot of sterilization data was pulled out of thin air. When looking through the articles that gave data about the sterilization in combination with a device [7], [18-22]. Most of the articles [24], [23], [22], [7], [20] stated that they used a database like Ecoinvent or European life cycle database for the data. Leiden et al. (2020) [21] on the other hand got their data from Ecoinvent except the washer and disinfection figures which came from own power measurements, witch they unfortunately did not specify. This article introduces the problem for this kind of research. What I have found during the literature research is that not much information is available about the environmental footprint of steam sterilisation system alone, [16] states the same.

information about the CSSD was rather limited, some research [14],[13],[23] focused only on the total water consumption. While another research [18],[19] focused clearly on one cycle of sterilization without giving a number of year round operation. This different approach made the connection of dots to gain an overview difficult.

During the search on the sterilization devices and washer disinfection machines information was search about the flow rate of water. Unfortunately, due to the limitations of the found articles no answer was found. Even if an answer was found there exist numbers of different machines with different specific programs. Therefore the flow rates of the drainage water in relevance with the heat exchanger flow rates was not combined. I would suggest to install a flow, temperature, power and gas meter in the installation to gain real time knowledge about the usage and were exactly improvements are possible. As stated in the discussion of the article written by Van Straten et al. (2021) [7] I agree with their final statements. With loads of articles the amount of capacity filling of the machines are not taken into account. With can drastically increase the total CO2 production of reusable devices due to the fact that the total production of CO2 per washing or sterilization cycle is divided by less instruments.

A lot of information was found of the heat exchangers were about efficiency improvements [18], [27],[54],[46]. The plate heat exchangers [45],[46],[47] had some resemblance of research, while on the other hand the tube and shell heat exchangers are able to be modified in an almost limitless way [48],[50],[54],[55],[57] this resulted in a search to find rather similar articles to compare the important aspect of the tube and shell heat exchanger.

There exist heaps amount of different types of heat exchangers but it was important to keep the search comprehensible. Therefor it is chosen to only search information about the two most used heat exchangers. Coil heat exchanger was also an option to find more information about. The Large limitation of a coil heat exchanger is that a large vat is needed, with a limited space left near/in the machine this was no practical option to find information about.

There is a lot of research done to make the hospitals and its departments more green. For the sterilizer and washing machine this is the same, with literature stating all kinds of helpful improvement to decrease the carbon emission. The abstract of all these articles seems to provide promising information. A lot of improvements in regards of establish a lower carbon emission is about typical operation equipment or surgical tray types like a different design of tray or a better tray assemblage or less instruments, different blue wrap [28], [29], [17]. It is noticed that a lot of articles [30] showed reduction in CO2 emission of hospitals by usage of using less instruments during surgery thus minimising the need for sterilization. Also a lot of information was found on the steam sterilization treatment of waste [62]. The efficiency improvements stated in the articles [48],[54], of the tube and shell heat exchangers stated to use an not round tube. What they did not specify was the cost it would induce to replace a round tube, not only the tube need to be altered from its fabricated form, but also the holes cannot be drilled with normal drill bits. Fetuga et al. (2023) [48] also stated that most literature focused only on heat transfer enhancement, with not much interest in the designing of heat exchanger to recover waste heat. For future research I would suggest to conduct a research about the water flow characteristics of the washing machine and the autoclave. An additional power measurement would also provide very useful information that is not provided by the literature these days. The number of a flow rate can influence the attractiveness of certain heat exchange articles with the same flow.

VIII. Conclusion

The goal for this literature study was to gain knowledge about the Carbon emission, water and electricity consumption of the CSSD. About 31 % of the total consummation of gas in a hospital can be contributed to the CSSD. Regarding the water consumption, the literature study found that the CSSD consumes a significant amount about 20% of water due to the cleaning and sterilization processes. To gain insight in the total carbon emission of the sterilization procedure a search is done to determine the partial influence of the sterilization process per lifetime of reusable instrument. This results in between 70% and 95% of the total Carbon emissions of a lifetime use of a reusable instrument is resulted from cleaning and sterilization. The other 5% to 30% of the Carbon emissions from reusable instruments is from manufacturing, shipping, repair, etc.

In literature it is stated that the two most used heat exchangers are the plate heat exchanger and the tube shell heat exchanger. Both heat exchangers are being investigated for their potential and limitations. The great advantageous about the plate heat exchanger is it compactness, the advantageous with the shell-tube heat exchanger is cheaper in operation costs. Both heat exchangers can reduce the gas usage of the CSSD up to 21%.

An optimal chevron angle for the plates in a PHEX is 30 degree and the surface roughness about 2.77 μm to optimise the efficiency. In the design of the STHEX the baffles has a high contribution towards the efficiency of the system. A flowering three piece baffle with inclination between 30 degree and 40 degree would result in the highest efficiency.

In the article the use of heat exchanger is proposed as a way to reduce gas consumption in the CSSD. Overall, the use of a water heat exchanger in the CSSD can lead to significant energy savings and cost reductions. The choice of heat exchanger should take into consideration factors such as cost effectiveness, space constraints and efficiency. If a choice is made which type of heat exchanger is chosen, the design can be made with help of either a Wilson plot or with the Kern or Bell-Delaware method.

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